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POLICY OPTIONS FOR STABILIZING GLOBAL CLIMATE

DRAFT

REPORT TO CONGRESS

Executive Summary

United States Environmental Protection Agency

Office of Policy, Planning, and Evaluation

February 1989

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Editors: Daniel A. Lashof and Dennis A. Tirpak

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation

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ACKNOWLEDGEMENTS

This report would not have been possible without the tireless efforts of the primary chapter authors:

Executive Summary	Daniel Lashof Dennis Tirpak
Chapter I. Introduction	Joel Scheraga Irving Mintzer
Chapter II. Greenhouse Gas Trends	Inez Fung Michael Prather
Chapter III. Climatic Change	Daniel Lashof Alan Robock
Chapter IV. Human Activities Affecting Trace Gases and Climate	Barbara Braatz Craig Ebert
Chapter V. Thinking About the Future	Daniel Lashof Leon Schipper
Chapter VI. Sensitivity Analyses	Craig Ebert
Chapter VII. Technical Control Options	Paul Schwengels (Energy Services) Michael Adler (Renewable Energy) Dillip Ahuja (Biomass) Kenneth Andrasko (Forestry) Lauretta Burke (Agriculture) Craig Ebert (Energy Supply) Joel Scheraga (Energy Supply) John Wells (Halocarbons)
Chapter VIII. Policy Options	Alan Miller
Chapter IX. International Cooperation to Reduce Greenhouse Gas Emissions	Alan Miller Jayant Sathaye
Appendix A. Model Descriptions	William Pepper
Appendix B. Scenario Definitions	Craig Ebert
Appendix C. Results of Sensitivity Analyses	Craig Ebert

Model integration was coordinated by William Pepper and Craig Ebert, with assistance from Rossana Florez. Models and/or analysis were prepared by Irving Mintzer; Jayant Sathaye, Andrea Ketoff, Leon Schipper, and Sharad Lele; Klaus Frohberg and Phil Vande Kamp; Richard Houghton; Berrien Moore, Chris Ringo, and William Emmanuel; Michael Prather; Ivar Isaksen, Terje Berntsen, and Sverre Solberg; and Anne Thompson.

Document integration was coordinated by Craig Ebert and Barbara Braatz. Editorial assistance was provided by Susan MacMillan. Technical, graphics, and typing assistance was provided by Courtney Dinsmore, Katey Donaldson, Donald Devost, Michael Green, Karen Zambri, Judy Koput, Donna Whitlock, Margo Brown, and Cheryl LaBrecque.

Literally hundreds of other people have contributed to this report, including the organizers and attendants at four workshops sponsored by EPA to gather information and ideas, and dozens of formal and informal reviewers. We would like to thank this legion for their interest in this project, and apologize for not doing so individually. Particularly important comments were provided by, among others, Thomas Bath, Deborah Bleviss, Gary Breitenbeck, William Chandler, Robert Friedman, Howard Geller, James Hansen, Tony Janetos, Stan Johnson, Julian Jones, Michael Kavanaugh, Andrew Lacis, Michael MacCracken, Elaine Matthews, William Nordhaus, Steven Piccot, Marc Ross, Stephen Schneider, Paul Steele, Pieter Tans, Thomas Wigley, Edward Williams, and Robert Williams.

This work was conducted within EPA's Office of Policy Analysis, directed by Richard Morgenstern, within the Office of Policy Planning and Evaluation, administered by Linda Fisher. Technical support was provided by the Office of Research and Development, administered by Eric Brethauer.

Review Draft

POLICY OPTIONS

FOR STABILIZING GLOBAL CLIMATE

Executive Summary

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    I. Uncertainties regarding climatic change are large, but there is a growing consensus in the scientific community that significant global warming due to anthropogenic greenhouse gas emissions is probable over the next century, and that rapid climatic change is possible. 83

    II. Measures undertaken to limit greenhouse gas emissions would decrease the magnitude and speed of global warming, regardless of uncertainties about the response of the climate system. 85

    III. No single country or source will contribute more than a fraction of the greenhouse gases that will warm the world; any overall solution will require cooperation of many countries and reductions in many sources. 87

    IV. A wide range of policy choices is available to reduce greenhouse gas emissions while promoting economic development, environmental, and social goals. 89

INTRODUCTION

The composition of the Earth's atmosphere is changing. There is a growing scientific consensus that the observed trends and projected increases in the atmospheric concentrations of greenhouse gases will alter the global climate. "Greenhouse" gases (carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide, among others) in the atmosphere absorb heat that radiates from the Earth's surface and emit some of this heat downward, warming the climate. Without this "greenhouse effect," the Earth would be about 30°C (60°F) colder than it is today. Human activities are now increasing the atmospheric concentrations of greenhouse gases on a global basis, thus intensifying the greenhouse effect. Although the specific rate and magnitude of future climate change is hard to predict, the rate of greenhouse gas buildup during the next century will depend heavily on future patterns of economic and technological development, which are, in turn, influenced by policies of local, state, national, and international private and public institutions.

Congressional Request for Reports

To better define the potential effects of global climate change and identify the options that are available to influence the composition of the atmosphere and the rate of climatic change, Congress asked the U.S. Environmental Protection Agency to undertake two studies on the greenhouse effect. In one of these studies Congress directed EPA to include:

> *"An examination of policy options that if implemented would stabilize current levels of atmospheric greenhouse gas concentrations. This study should address the need for and implications of significant changes in energy policy, including energy efficiency and development of alternatives to fossil fuels; reductions in the use of CFCs; ways to reduce other greenhouse*

> *gases such as methane and nitrous oxide; as well as the potential for and effects of reducing deforestation and increasing reforestation efforts."*

This report responds to that request. The second study was to focus on "the potential health and environmental effects of climate change." A companion report, *The Potential Effects of Climate Change on the United States*, responds to the second request.

This Executive Summary describes the goals established by EPA for this study, considering previous work and our Congressional mandate. The analytical framework developed for this study is briefly described and its limitations are noted. We then summarize current understanding of the greenhouse gases and their impact on global climate. A description of the scenarios that were developed to explore the sensitivity of the climate system to policy choices is presented next. The results of this scenario analysis follows, emphasizing the relative impact of various options. The technological and policy strategies that appear most promising for reducing greenhouse gas emissions are then presented by major activity category: energy production and use, other industrial activities, changes in land use, and agricultural practices. The policy options that are available for promoting these emission reduction strategies are then reviewed, giving consideration to the timing of policy responses to the greenhouse gas buildup. Finally, the major findings of this study are summarized.

Previous Studies

Atmospheric measurements indicating that the composition of the atmosphere is changing (e.g., Figure 1) have led to many assessments of the potential magnitude of future greenhouse gas emissions, future greenhouse gas concentrations, and associated climatic changes. A scientific consensus has emerged from these studies that increased concentrations of greenhouse gases will result in climate change. Moreover, there is serious risk that, in the absence of policy responses,

FIGURE 1

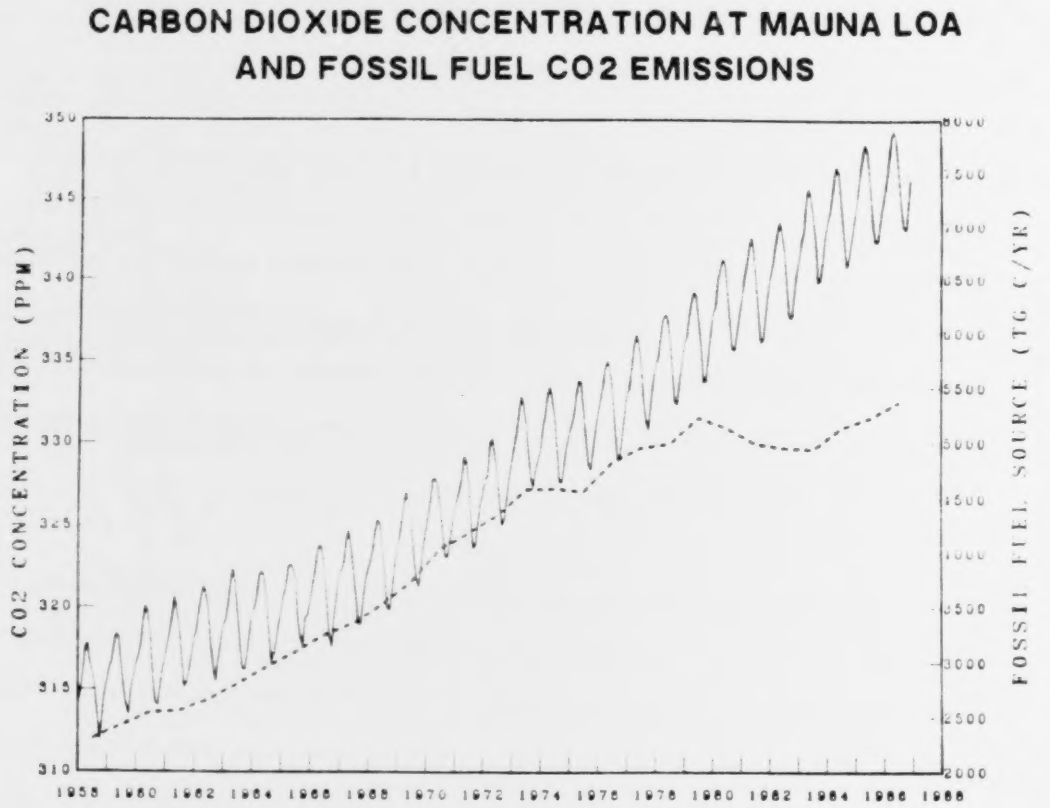

CARBON DIOXIDE CONCENTRATION AT MAUNA LOA AND FOSSIL FUEL CO2 EMISSIONS

Figure 1. The solid line depicts monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. The dashed line represents the annual emissions of CO_2, in units of carbon, due to fossil fuel combustion.

greenhouse gas emissions will continue to increase due to population and economic growth, and that sometime during the middle of the next century, the buildup of greenhouse gases will have a climatic effect equivalent to doubling the concentration of carbon dioxide from preindustrial levels.

A study by the U.S. National Academy of Sciences in 1979 concluded that doubling the concentration of carbon dioxide relative to the preindustrial atmosphere would result in an eventual (equilibrium) global warming of 1.5-4.5°C. Subsequent re-evaluations by the National Academy of Sciences (in 1983 and 1987), as well as the "State-of-the-Art" report issued by the U.S. Department of Energy in 1985, have reaffirmed this estimate. Recent general circulation model results and a recent review conducted for the international Scientific Committee On Problems of the Environment (SCOPE) suggest that a warming of 5.5°C as a result of doubling carbon dioxide may be at least as likely as a warming of 1.5°C.

Only a few studies have examined potential policy responses to the greenhouse gas buildup. The *IEA/ORAU Long-Term Global Energy CO_2 Model* developed for the Department of Energy in 1983 was used in many of these studies, including EPA's 1983 report, *Can We Delay a Greenhouse Warming?* This study investigated the extent to which policy measures might influence the timing of a 2°C global warming. The IEA/ORAU model was also used for important studies conducted at the Massachusetts Institute of Technology Energy Laboratory (in 1984) and the World Resources Institute (in 1987). These studies concluded that policy choices could have a major influence on the total warming that may be experienced during the next century.

Goals of this Study

Congress presented EPA with a very challenging task. From a policy perspective, it is not enough to know how emissions would have to change from current levels in order to stabilize the atmosphere. Instead, policy options must be evaluated in the context of expected economic and technological development and the uncertainties that prevent us from knowing precisely how a given level of emissions will impact the rate and magnitude of climate change. It is also necessary that the scope of this study be global and the time horizon be more than a century, because of the long lags built into both the economic and climatic systems (we chose 1985-2100 as the time frame for the analysis). We cannot predict what the future will bring, but scenarios can be developed to explore policy options.

Based on these considerations EPA established four major goals:

- To assemble data on global trends in emissions and concentrations of all major greenhouse gases and activities that affect these gases.
- To develop an integrated analytical framework to study how different assumptions about the global economy and the climate system could influence future greenhouse gas concentrations and global temperatures.
- To identify promising technologies and practices that could limit greenhouse gas emissions.
- To identify policy options that could influence future greenhouse gas concentrations and global warming.

Approach Used to Prepare this Report

To achieve these goals EPA conducted an extensive literature review and data gathering process. The Agency held several informal panel meetings, and enlisted the help of leading experts in the governmental, non-governmental, and academic research communities. EPA also conducted five workshops, which were attended by over three hundred people, to gather information and ideas regarding factors affecting atmospheric composition and options related to greenhouse gas emissions from agriculture and land-use change, electric utilities, end-uses of energy, and developing countries. Experts in NASA, the Department of Energy, and the Department of Agriculture were actively engaged.

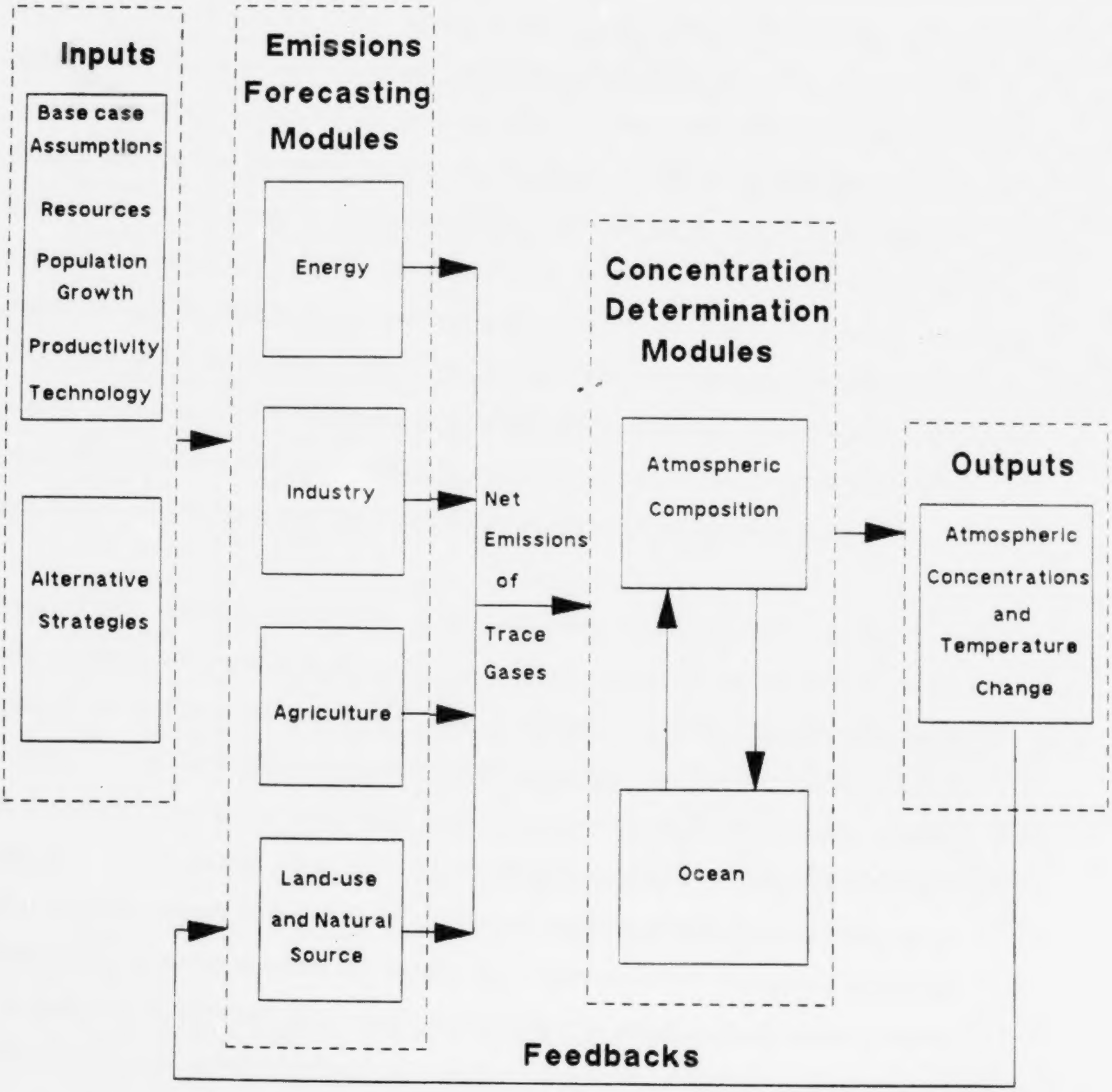
Based on the outcome of this process, EPA developed an integrated analytical framework to organize the data and assumptions required to calculate (1) emissions of radiatively and chemically active gases, (2) concentrations of greenhouse gases, and (3) changes in global temperatures. This framework is highly simplified, as its primary purpose is to rapidly scan a broad range of policy options in order to test their general effectiveness in reducing atmospheric concentrations of greenhouse gases. It is the first attempt to relate the underlying forces (e.g., population growth, economic growth, and technological change) to the emissions of all the important greenhouse gases. This framework makes it possible to estimate the impact of changes in these factors on the composition of the atmosphere and global temperatures. In constructing this framework, we used the results of more sophisticated models of individual components as a basis for our analysis. While we believe that this framework generally reflects the current state of scientific knowledge, there are important limitations (discussed below) that may affect the results of our analysis.

Emissions of the greenhouse gases CO_2, CH_4, N_2O, and of a number of halocarbons are explicitly calculated within the framework based on assumptions about activities that generate these gases, such as energy production and consumption, industrial processes, agricultural practices, and deforestation. Emissions of CO and NO_x, which are not themselves greenhouse gases, are also explicitly calculated, as these gases can significantly alter the chemistry of the atmosphere and thus affect the concentrations of the greenhouse gases. The four emissions modules (Figure 2) use input data, including scenario specifications, for population growth, GNP, energy efficiency, agricultural productivity, and the rate of deforestation. The Energy Module is based on the *IEA/ORAU Long-Term Global Energy CO_2 Model* developed for the U.S. Department of Energy (modified considerably for this study), and on analysis of energy end-use patterns conducted by Lawrence Berkeley Laboratory and the World Resources Institute. EPA's CFC model, developed to assess stratospheric ozone depletion, forms the primary component of the Industry Module. The Agriculture Module is based on the Basic Linked System developed at the International Institute of Applied Systems Analysis and emissions coefficient estimates from the literature; and the Land-Use and Natural Source Module uses the Terrestrial Carbon Model developed at the Woods Hole Marine Biological Laboratory for CO_2 emissions related to deforestation. Emissions are estimated for nine regions of the globe and are calculated every 5 years from 1985 to 2025 and then every 25 years through 2100.

In addition to the emissions modules, there are two concentration modules. Together these concentration modules estimate changes in global atmospheric concentrations of the greenhouse gases based on the projected emissions and changes in global temperatures that result from the calculated concentrations. The Atmospheric Composition Module consists of a highly simplified model of global chemistry developed by NASA and a parameterization of the impact of changes in greenhouse gas concentrations on the radiation balance of the Earth. The Ocean Module contains a modified version of the Goddard Institute for Space Studies ocean model that simultaneously calculates carbon dioxide and heat uptake. The Ocean Module also contains four additional models for carbon dioxide uptake assembled by the Complex Systems Research Center at the University of New Hampshire. The calculated atmospheric trace-gas concentrations and temperature changes affect the emissions

FIGURE 2

STRUCTURE OF THE ATMOSPHERIC STABILIZATION FRAMEWORK


Inputs
Base case Assumptions
Resources
Population Growth
Productivity
Technology
Alternative Strategies
Emissions Forecasting Modules
Energy
Industry
Agriculture
Land-use and Natural Source
Net Emissions of Trace Gases
Concentration Determination Modules
Atmospheric Composition
Ocean
Outputs
Atmospheric Concentrations and Temperature Change
Feedbacks

modules in the next time period. The estimates of global temperature change serve as indicators for the rate and magnitude of global change, but it is important to keep in mind that changes in precipitation and other factors may be as important as changes in global temperature, and that the timing and magnitude of climatic changes at a regional level may differ significantly from the global average.

Limitations

This analytical framework attempts to incorporate some representation of the major processes that will influence the rate and magnitude of greenhouse warming during the next century within a structure that is reasonably transparent and easy to manipulate. In so doing we recognize a number of major limitations:

- Economic growth rates are difficult to forecast and will strongly influence future greenhouse gas emissions. Although there are factors cutting in both directions, emissions can generally be expected to be higher if economic growth is more rapid. Our alternative assumptions may not adequately reflect the plausible range of possible growth rates.

- Economic linkages are not fully captured. The type of economic analysis conducted cannot ensure that the activity levels assumed in each sector are completely consistent with the aggregate economic assumptions. In addition, capital markets are not explicitly considered. This is particularly significant with regard to developing countries, as it is unclear if they will be able to obtain the capital needed to grow as fast or develop the energy supplies assumed in some of the scenarios.

- Technological changes are difficult to forecast. Substantial improvements in the efficiency of energy-using and energy-producing technologies are assumed to occur even in the absence of substantial energy price increases or policy measures. If this assumption proves to be untrue, then greenhouse gas emissions may be substantially underestimated in the No Response scenarios (see below for the scenario definitions). Similarly, aggressive research and development is assumed to substantially reduce the cost of renewable technologies in the Stabilizing Policy scenarios. The impact of policies may be overestimated if such improvements fail to materialize or if they would have materialized as rapidly even without increased government support.

- Detailed cost analyses have not been conducted. Technological strategies have been screened based on judgments about their potential to be cost-effective, but no attempt has been made to rank the cost-effectiveness of each strategy or to estimate the government expenditures or total social costs or benefits associated with the stabilizing strategies.

- The modules of the framework are not fully integrated. Existing models of individual processes that affect greenhouse gas emissions were assembled within the analytical framework and were used with consistent assumptions. However, it was not possible to ensure complete consistency of results. For example, while the biomass energy supplies arrived at in the Energy Module do not appear to be inconsistent with the land use patterns calculated in the

Agriculture and Land Use and Natural Source Modules, there is no explicit coupling among these results.

- The ocean models employed, are highly simplified. The ocean plays an important role in taking up both CO_2 and heat. The one-dimensional models used to represent this process may not adequately reflect the underlying physical processes, particularly as climate changes.

- Changes in atmospheric chemistry are calculated in a highly simplified fashion. Chemical interactions are analyzed based on parameters derived from detailed chemical models. These parameters may not adequately reflect the underlying chemistry, particularly as the atmospheric composition changes significantly from current conditions. Also, it is not possible to explicitly model the heterogeneous conditions that control, for example, tropospheric ozone concentrations. In our analysis we also assume that non-methane hydrocarbon emissions remain constant, which may cause future methane and ozone changes to be underestimated.

HUMAN IMPACT ON THE CLIMATE SYSTEM

The Greenhouse Gas Buildup

Many greenhouse gases are currently accumulating in the atmosphere. The most important is carbon dioxide (CO_2), followed by methane (CH_4), chlorofluorocarbons (CFCs), and nitrous oxide (N_2O) (Figure 3). Carbon dioxide is a fundamental product of burning fossil fuels (coal, oil, and gas), and is also released as a result of deforestation (Box 1). The largest methane source is decay

FIGURE 3

GREENHOUSE GAS CONTRIBUTIONS TO GLOBAL WARMING

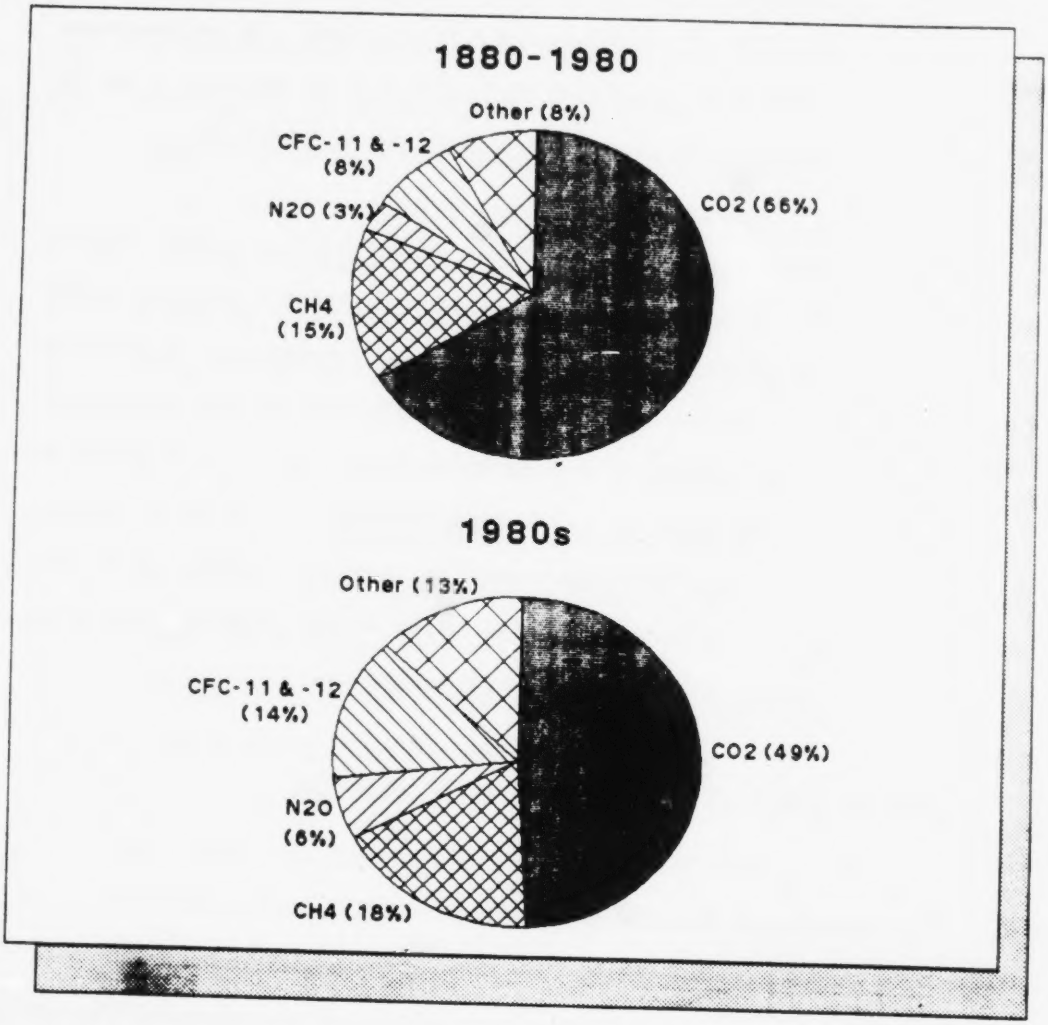


Figure 3. Based on estimates of the increase in the concentration of each gas during the specified period. Other includes additional CFCs, halons, changes in ozone, and changes in stratospheric water vapor. The other category is quite uncertain.

of organic matter in the absence of oxygen, while CFCs are produced only by the chemical industry. The sources of nitrous oxide are not well characterized, but most are probably related to soil processes.

Stabilizing emissions of greenhouse gases at current levels will not stabilize concentrations. Once emitted, greenhouse gases remain in the atmosphere for decades to centuries. At current emission levels, greenhouse gases are being released into the atmosphere faster than they are being removed. As a result, if emissions remained constant at 1985 levels, the greenhouse effect would continue to intensify for more than a century. Carbon dioxide concentrations would reach 440-500 parts per million (ppm) by 2100, compared with about 350 ppm today, and about 290 ppm 100 years ago (Figure 4). CFC concentrations would increase by more than a factor of three from current levels, while nitrous oxide concentrations would increase by about 20%, and methane concentrations might remain roughly constant.

Drastic cuts in emissions would be required to stabilize atmospheric composition as shown in Table 1 (see also, Box 1), and even if all anthropogenic emissions of CO_2, CFCs, and N_2O were eliminated the concentrations of these gases would remain elevated for decades. It would take more than 50 years, and possibly more than a century, for the oceans to absorb enough carbon to reduce the atmospheric concentration of CO_2 half way toward its preindustrial value. It would also take more than 50 years before excess concentrations for CFCs and N_2O declined by half after all anthropogenic emissions were eliminated.

FIGURE 4

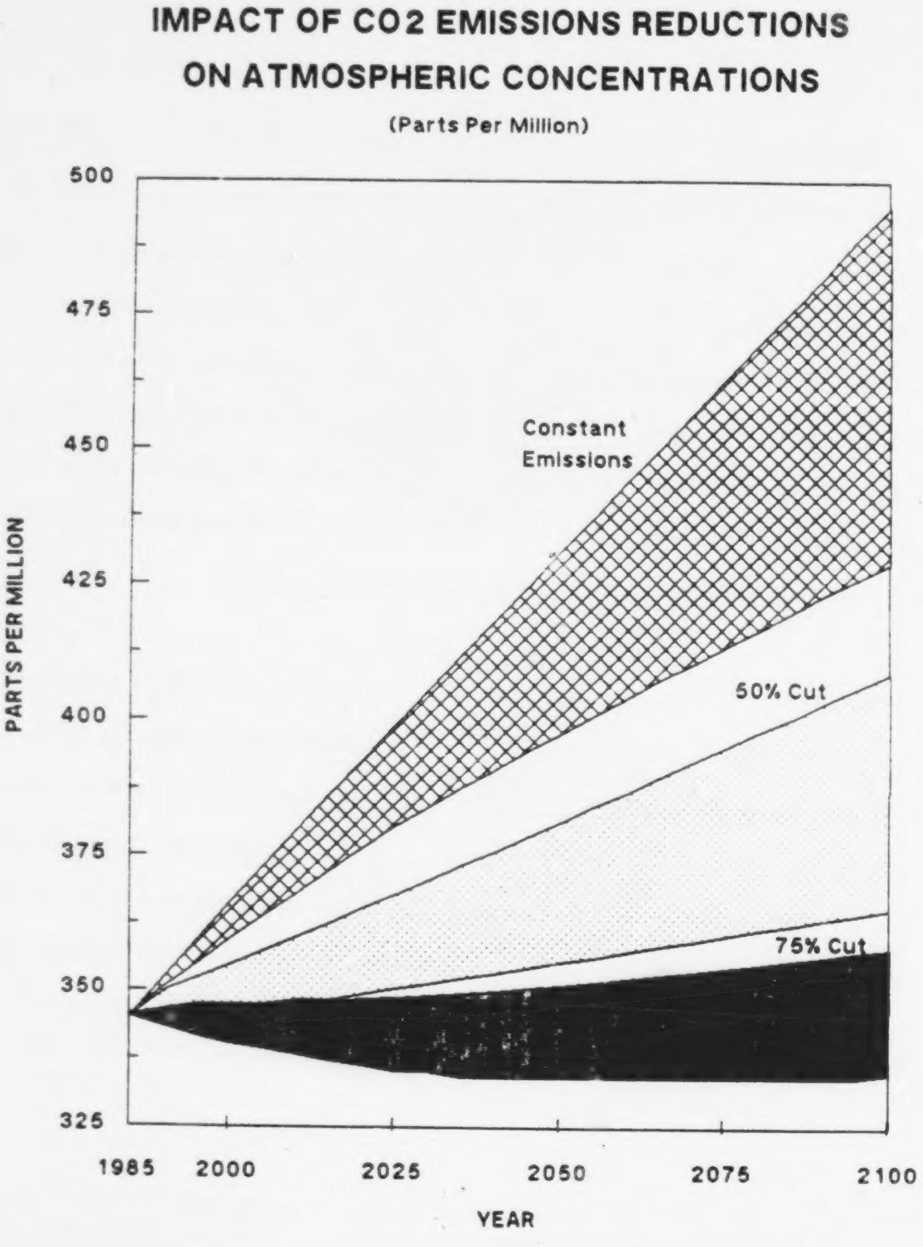


Figure 4. The response of atmospheric CO_2 concentrations to arbitrary emissions scenarios, based on two one-dimensional models of ocean CO_2 uptake. The emissions scenarios are relative to estimated 1985 levels of 5.9 billion tons of carbon per year.

TABLE 1

Approximate Reductions in Anthropogenic Emissions Required to Stabilize Atmospheric Concentrations at Current Levels

GAS	REDUCTION REQUIRED
Carbon Dioxide (CO_2)	50-80%
Methane (CH_4)	10-20%
Nitrous Oxide (N_2O)	80-85%
Chlorofluorocarbons (CFCs)	75-100%
CO, NO_x	Freeze

BOX 1

The Greenhouse Gases

Carbon dioxide. Carbon dioxide (CO_2) is the most abundant and single most important greenhouse gas in the atmosphere. Its concentration has increased by about 25% since the industrial revolution. Detailed measurements since 1958 show an increase from 315 to 350 parts per million by volume (Figure 1). Carbon dioxide concentrations are currently increasing at a rate of about 0.4% per year, which is responsible for about half of current increases in commitment to global warming from greenhouse gas buildup (Figure 3). Both deforestation and fossil-fuel combustion have contributed to this rise. Current emissions are estimated at 5.5 billion tons of carbon (Pg C) from fossil-fuel combustion and 0.4-2.6 Pg C from deforestation. Most of this carbon dioxide remains in the atmosphere or is absorbed by the oceans. Even though only about half of current emissions remain in the atmosphere, available models of CO_2 uptake by the ocean suggest that substantially more than a 50% cut in emissions is required to stabilize concentrations at current levels.

Methane. The concentration of methane (CH_4) has more than doubled during the last three centuries. Methane, which is currently increasing at a rate of 1% per year, is responsible for about 20% of current increases in commitment to global warming. There is considerable uncertainty about the sources of methane, and the observed increase is probably due to increases in a number of sources as well as to changes in tropospheric chemistry. Increases in agricultural sources, particularly rice cultivation and animal husbandry, have probably been the most significant factor, but emissions from landfills and coal seams could play an important role in the future. Of the major greenhouse gases only methane concentrations can be stabilized with modest cuts in anthropogenic emissions: a 10-20% cut would suffice to stabilize concentrations at current levels due to methane's relatively short atmospheric lifetime, assuming that this lifetime remains constant and that natural emissions do not change. Whether this is the case will depend on changes in tropospheric chemistry as influenced by emissions of hydrocarbons and carbon monoxide, among others, and on whether global climate change itself affects methane emissions.

Nitrous oxide. The concentration of nitrous oxide (N_2O) has increased by 5-10% since preindustrial times. The cause of this increase is highly uncertain, but it appears that the use of nitrogenous fertilizer, land clearing, biomass burning, and fossil-fuel combustion have all contributed. Each additional molecule of nitrous oxide has over 200 times as much impact on climate as additional molecules of carbon dioxide, and nitrous oxide can also contribute to stratospheric ozone depletion. Nitrous oxide is currently increasing at a rate of 0.25% per year, which represents an imbalance of about 30% between total emissions and total losses. Nitrous oxide increases are responsible for roughly 6% of current increases in commitment to global warming. Assuming that the observed increase in N_2O concentrations is due to anthropogenic sources and that natural emissions have not changed, then an 80-85% cut in anthropogenic emissions would be required to stabilize N_2O at current levels.

Halocarbons. Chlorofluorocarbons (CFCs), currently the most important halocarbons, were introduced into the atmosphere for the first time during this century. The most common species are CFC-12 (CCl_2F_2) and CFC-11 (CCl_3F), which had atmospheric concentrations in 1986 of 392 and 226 parts per trillion by volume, respectively. While these concentrations are tiny compared with that of CO_2, CFCs have as much as 20,000 times more impact on climate per additional molecule and are increasing very rapidly--more than 4% per year since 1978. A focus of attention because of their potential to deplete stratospheric ozone, the increasing concentration of CFCs also represents about 15% of current increases in commitment to global warming. For CFC-11 and CFC-12, cuts of 75% and 85%, respectively, of current global emissions would be required to stabilize concentrations. However because of growth in other compounds, in order to stabilize the total greenhouse warming potential from all halocarbons, a phaseout of the fully halogenated compounds (those that do not contain hydrogen), a freeze on the use of methyl chloroform, and a limit on the emissions of partially halogenated substitutes would be required.

Other gases influencing composition. Emissions of carbon monoxide (CO) and nitrogen oxides (NO_x), among other species, in addition to the greenhouse gases just described, are also changing the chemistry of the atmosphere. This change in atmospheric chemistry alters the distribution of ozone and the oxidizing power of the atmosphere, changing the atmospheric lifetimes of the greenhouse gases. If the concentrations of the long-lived gases were stabilized, it might only be necessary to freeze emissions of the short-lived gases at current levels to stabilize atmospheric composition.

In preparing this report, EPA did not develop scenarios that achieve zero change in concentrations, instead we have focused on promising options that can significantly slow the rate of greenhouse gas buildup and climatic change.

The Impact of Greenhouse Gases on Global Climate

Uncertainties about the impact of the greenhouse gas buildup on global climate abound. These uncertainties are not about whether the greenhouse effect is real or whether increased greenhouse gas concentrations will raise global temperatures. Rather, the uncertainties concern the ultimate magnitude and timing of warming and the implications of that warming for the Earth's climate system, environment, and economies.

The magnitude of future global warming will depend, in part, on how geophysical and biological feedbacks enhance the warming caused by the additional infrared radiation absorbed by increasing concentrations of greenhouse gases. The ultimate global average temperature increase that can be expected from a specific increase in the concentrations of greenhouse gases can be called the "climate sensitivity." This parameter provides a convenient index for the magnitude of climatic change that would be associated with different scenarios of greenhouse gas buildup. (In this report we use a doubling of the concentration of CO_2 from preindustrial levels, or the equivalent from increases in the concentrations of a number of greenhouse gases, as the benchmark case.)

Estimating the impact of increasing greenhouse gas concentrations on global climate has been a focus of research within the atmospheric science community for more than a decade.

- If nothing else changed in the Earth's climate system except the doubling of CO_2 (or the equivalent in other greenhouse gases), average global temperature would rise 1.2-1.3°C.

- A strong scientific consensus exists that increased global temperatures would raise atmospheric levels of water vapor and change the vertical temperature profile, raising the ultimate global warming caused by a doubling of CO_2 to 1.8-2.5°C, if nothing other than these factors changed in the Earth's climate system. Changes in snow and ice cover are also expected to enhance warming, raising the estimate to 2-4°C.

- General Circulation Models now generally project that the global warming from doubling CO_2 would cause changes in clouds that could enhance this warming to roughly 2.5 to 5.5°C. Uncertainties exist about this feedback, however. There also exists the possibility that the cloud feedback will be negative and would diminish the warming somewhat, perhaps to 1.5°C.

- A variety of other geophysical and biogenic feedbacks exist that have generally been ignored in global climate models. For example, future global warming has the potential to increase emissions of carbon from northern latitude reservoirs in the form of both methane and carbon dioxide, and to alter uptake of CO_2 by the biosphere and the oceans. When all such feedbacks are considered, it is possible that the actual climate sensitivity of the Earth could exceed 5.5°C for an initial doubling of CO_2.

Global warming of just a few degrees would represent a enormous change in climate. The difference in mean annual temperature between Boston and Washington is only 3.3°C, and the difference between Chicago and Atlanta is 6.7°C. The total global warming since the peak of the last ice age, 18,000 years ago, was only about 5°C. That change transformed the landscape of North America; it shifted the Atlantic ocean inland by about one-hundred miles, created the Great Lakes, and changed the composition of forests throughout the continent.

The potential future impacts of climatic change are difficult to predict and are beyond the scope of this report. Sensitivity analyses can be undertaken to estimate potential impacts, as was done in the companion volume, *The Potential Effects of Global Climate Change on the United States*. The findings of that study collectively suggest that the climatic changes associated with a global warming of roughly 2-4°C would result in "a world that is different from the world that exists today. Global climate change will have significant implications for natural ecosystems; for when, where, and how we farm; for the availability of water to drink and water to run our factories; for how we live in our cities; for the wetlands that spawn our fish; for the beaches we use for recreation; and for all levels of government and industry."

SCENARIOS FOR POLICY ANALYSIS

Defining Scenarios

Defining scenarios that encompass more than a century is a daunting task. While this is an eternity for most economists and planners, it is but a moment for geologists. And indeed, decisions made in the next few decades, about how buildings are constructed, electricity is generated, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. Decisions about what kinds of automobiles and other industrial products to produce and how to produce them will also have a profound impact. These choices, which will affect the amount and type of fuel we use to travel, to heat and light our homes and offices, and to run our factories, will influence the magnitude of greenhouse gas emissions for many years.

To explore the climatic implications of such policy and investment decisions, we have constructed four scenarios of future patterns of economic development and technological change. These scenarios start with alternative assumptions about the rate of economic growth and policies that influence emissions. These scenarios are intended to be internally consistent pictures of how the world may evolve in the future. They are not forecasts and they do not bracket the full range of possible futures. Instead, they were chosen to provide a basis for evaluating strategies for stabilizing the atmosphere in the context of distinctly different, but plausible, conditions.

Two scenarios explore alternative pictures of how the world may evolve in the future assuming that policy choices allow unimpeded growth in emissions of greenhouse gases (these are referred to as the "No Response" scenarios). One of these scenarios, called a Rapidly Changing World (RCW), assumes rapid economic growth and technical change; the other, called the Slowly Changing World (SCW), represents a slower evolution of the world's economies. Two additional scenarios (referred to as the "Stabilizing Policy" scenarios) start with the same economic and demographic assumptions, but assume a world in which policies to limit anthropogenic emissions have been adopted. These scenarios are called the Slowly Changing World with Stabilizing Policies (SCWP) and the Rapidly Changing World with Stabilizing Policies (RCWP). An overview of the scenario assumptions is given in Table 2. In all of the scenarios it is assumed that the key national and international political institutions evolve gradually, with no major upheavals.

The various assumptions that go into these scenarios are conceptually consistent, which leads to partially offsetting impacts on greenhouse gas emissions. For example, more rapid economic growth in the RCW compared to the SCW scenario is assumed to be associated with more rapid technological innovation and replacement of older equipment, which has higher greenhouse gas emissions. Similarly, rapid increases in income are assumed to be associated with more rapid decreases in population growth rates. In the Stabilizing Policy scenarios it is assumed that more rapid reductions in greenhouse gas emissions per unit of activity are possible when economic growth rates are higher. If such offsetting tendencies do not occur, and/or if economic growth is more rapid than assumed in the RCW and RCWP scenarios, then the rate of greenhouse gas buildup would

TABLE 2

Overview of Scenario Assumptions

Slowly Changing World	Rapidly Changing World
Slow GNP Growth	Rapid GNP Growth
Continued Rapid Population Growth	Moderated Population Growth
Minimal Energy Price Increases	Modest Energy Price Increases
Slow Technological Change	Rapid Technological Improvements
Carbon-Intensive Fuel Mix	Very Carbon-Intensive Fuel Mix
Increasing Deforestation	Moderate Deforestation
Montreal Protocol/Low Participation	Montreal Protocol/High Participation

Slowly Changing World with Stabilizing Policies	Rapidly Changing World with Stabilizing Policies
Slow GNP Growth	Rapid GNP Growth
Continued Rapid Population Growth	Moderated Population Growth
Minimal Energy Price Increases/Taxes	Modest Energy Price Increases/Taxes
Rapid Efficiency Improvements	Very Rapid Efficiency Improvements
Moderate Solar/Biomass Penetration	Rapid Solar/Biomass Penetration
Rapid Reforestation	Rapid Reforestation
CFC Phase-Out	CFC Phase-Out

probably be higher than what is calculated for these scenarios. Economic growth may also be lower than is assumed in the SCW.

The analysis for this study included a detailed examination of energy demand for the year 2025. We chose this date because, although substantial change will have occurred, some infrastructure will still be in place and much of the technology to be deployed over this period is already under development. Scenarios extending beyond this date are speculative, but they are included because they are necessary to evaluate the full implications of more immediate decisions and because greenhouse gases affect warming for many decades. Projections to 2100 are based on the patterns and relationships established between 1985 and 2025. Our procedure is to consider the major economic and social structures that determine the activities that give rise to trace-gas emissions.

Scenarios with Unimpeded Emissions Growth

In "A Slowly Changing World" (SCW) we consider the possibility that the recent experience of modest growth will continue indefinitely, with no concerted policy response to the risk of climatic change. In this scenario we assume that the aggregate level of economic activity (as measured by GNP) increases relatively slowly on a global basis. Per capita income is stagnant for some time in the developing regions that have very high population growth, with modest increases elsewhere. Per capita economic growth rates increase slightly over time in all developing regions as population growth rates gradually decline. The population engaged in traditional agriculture continues to increase, as does demand for fuelwood and speculative land clearing. These factors lead to accelerated deforestation until tropical forests are virtually eliminated toward the middle of the next century. Because of slack demand, real energy prices increase slowly. Correspondingly, existing capital stocks turn over slowly and production efficiency in agriculture and industry improves at only a moderate rate. The energy efficiency of buildings, vehicles, and consumer products also improve at a slow rate.

In "A Rapidly Changing World" (RCW) rapid economic growth and technological change occurs with little attention given to the global environment. Per capita income rises rapidly in most regions and consumers demand increasing energy services, which puts upward pressure on energy prices. The number of cars increases rapidly in developing countries and air travel increases rapidly in industrialized countries. Energy efficiency is not much of a consideration in consumer choices, as income increases faster than real energy prices, but efficiency increases occur due to technological improvements. Correspondingly, we assume that there is a high rate of innovation in industry and that capital equipment turns over rapidly, thereby accelerating reductions in energy required per unit of industrial output. An increasing share of energy is consumed in the form of electricity, which is produced mostly from coal. The fraction of global economic output produced in the developing countries increases dramatically as services become more important in industrialized countries and as industries such as steel, aluminum, and auto-making grow in developing countries. Population growth rates decline more rapidly than in the Slowly Changing World scenario as educational and income levels rise. Deforestation continues at about current rates, spurred by land speculation and commercial logging, despite reduced rates of population growth.

The No Response scenarios examined lead to substantial greenhouse gas buildup and global warming. The two worlds described above lead to significant increases in carbon dioxide and trace gas emissions (Table 3), large increases in greenhouse gas concentrations (Figure 5), and substantial global warming. Carbon dioxide concentrations reach twice their preindustrial levels in about 2080 in the SCW scenario. In the RCW this level is reached by 2055, and concentrations more than three times preindustrial values are reached by 2100. Methane concentrations increase by almost a factor of 2 in the SCW and a factor of 2.6 in the RCW, with the

TABLE 3

Current and Projected Trace Gas Emissions Estimates

	1985	2025	2100
CO_2 (Pg C)[a]			
SCW	5.9	9.2	11.4
RCW	5.9	11.5	25.5
SCWP	5.9	5.1	3.1
RCWP	5.9	5.2	4.5
N_2O (Tg N)[b]			
SCW	11.3	13.5	12.1
RCW	11.3	13.0	15.0
SCWP	11.3	10.7	10.7
RCWP	11.3	10.8	10.9
CH_4 (Tg CH_4)			
SCW	514.4	676.4	815.9
RCW	510.5	712.4	1,089.0
SCWP	514.4	545.0	484.7
RCWP	510.5	558.7	508.0
NO_x (Tg N)			
SCW	53.3	68.8	70.1
RCW	53.2	72.9	118.2
SCWP	53.3	44.8	42.6
RCWP	53.2	50.7	43.8
CO (Tg C)			
SCW	502.3	842.0	603.5
RCW	502.0	699.1	1,207.1
SCWP	502.3	286.1	250.9
RCWP	502.0	290.8	244.9
CFC-12 (Gg)[c]			
SCW	363.8	379.7	410.8
RCW	363.8	437.5	493.1
SCWP	363.8	54.9	66.0
RCWP	363.8	85.9	86.6
CFC-22 (Gg)			
SCW	73.8	385.0	794.8
RCW	73.8	829.1	2,795.6
SCWP	73.8	385.0	794.8
RCWP	73.8	829.1	2,795.6

[a] 1 Pg C = 1 billion metric tons of carbon.

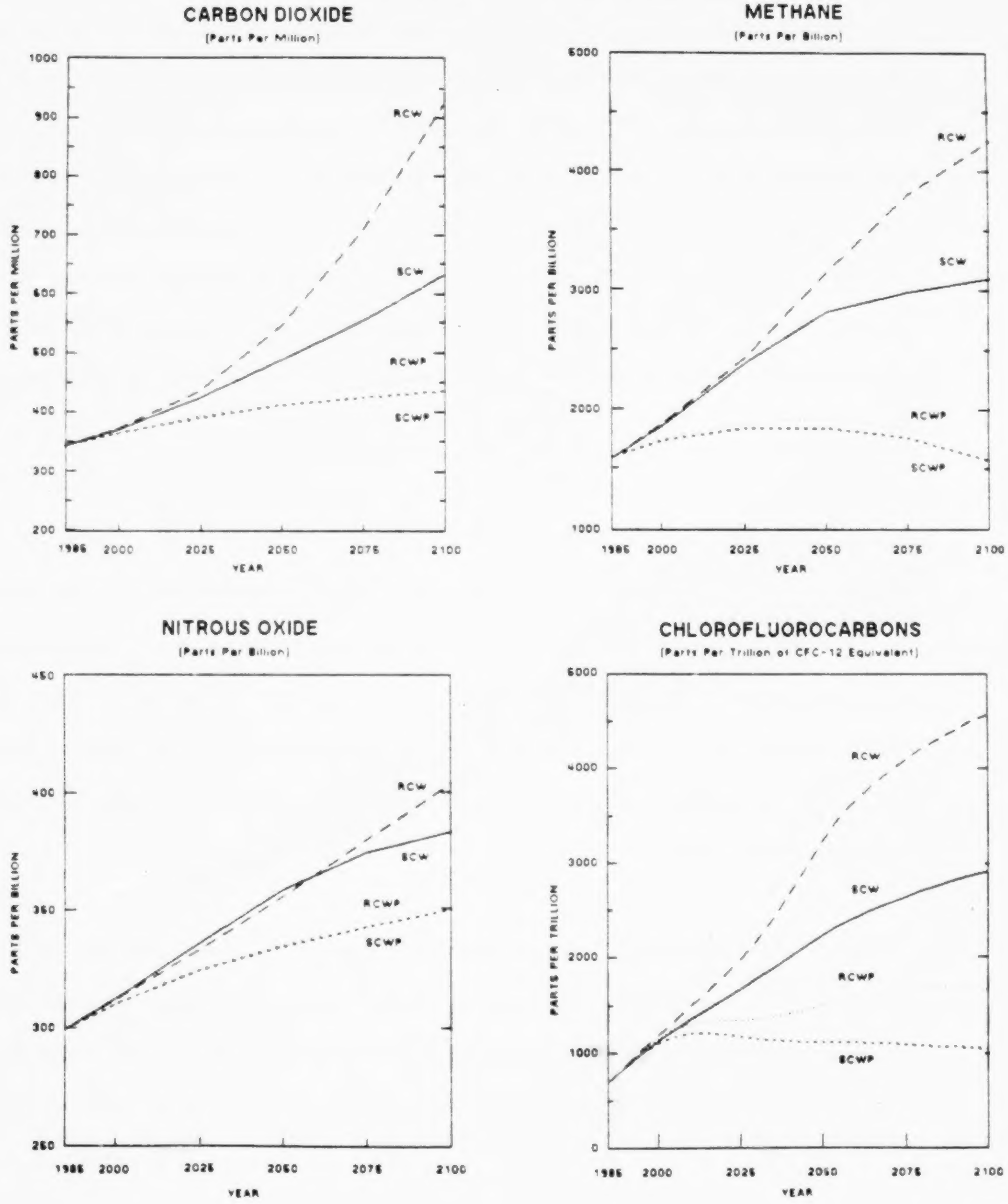
[b] 1 Tg N = 1 million metric tons of nitrogen.

[c] 1 Gg = 1 thousand metric tons = 1 million kilograms.

FIGURE 5

ATMOSPHERIC CONCENTRATIONS

(3.0 Degree Celsius Climate Sensitivity)



most rapid growth occurring between 1985 and 2050. The combined greenhouse effect of CFCs increases to a greater extent, reaching 4.2 times 1985 levels by 2100 in the SCW and 6.5 times 1985 levels in the RCW, despite assuming that at least 65% of developing countries and 95% of industrialized countries participate in the Montreal Protocol to control emissions of these compounds. Nitrous oxide concentrations also increase significantly, primarily as a result of the current imbalance between sources and sinks. When all the trace gases are considered, an increase in the greenhouse effect equivalent to that which would occur from a doubling of CO_2 concentrations is reached by 2040 in the SCW and by 2030 in the RCW. These results are in good agreement with recent studies that have made less formal estimates based primarily on current trends in concentrations and/or emissions. A notable exception is CFCs, for which we expect significantly lower concentrations as a result of the recent Montreal Protocol to control production of these compounds (see Production and Use of Halocarbons).

Even the Slowly Changing World scenario is calculated to produce a 2-3°C temperature increase during the next century. In the SCW scenario, realized global warming would increase by 1.0-1.5°C between 2000 and 2050 and by 2-3°C from 2000 to 2100 (temperature ranges are based on a climate sensitivity of 2-4°C unless otherwise noted; see Box 2; Figure 6). The maximum realized rate of change associated with this scenario is 0.2-0.3°C per decade, which occurs sometime in the middle of the next century. The total equilibrium warming commitment is substantially higher, reaching 3-6°C by 2100 relative to preindustrial levels.

Higher rates of economic growth are certainly the goal of most governments and could lead to higher rates of climatic change as illustrated by the RCW scenario. Compared with the SCW, the rate of change during the next century would be more than 50% greater in the RCW: In the RCW realized global warming increases by 1.2-1.9°C between 2000 and 2050, and by 3-5°C between 2000

FIGURE 6

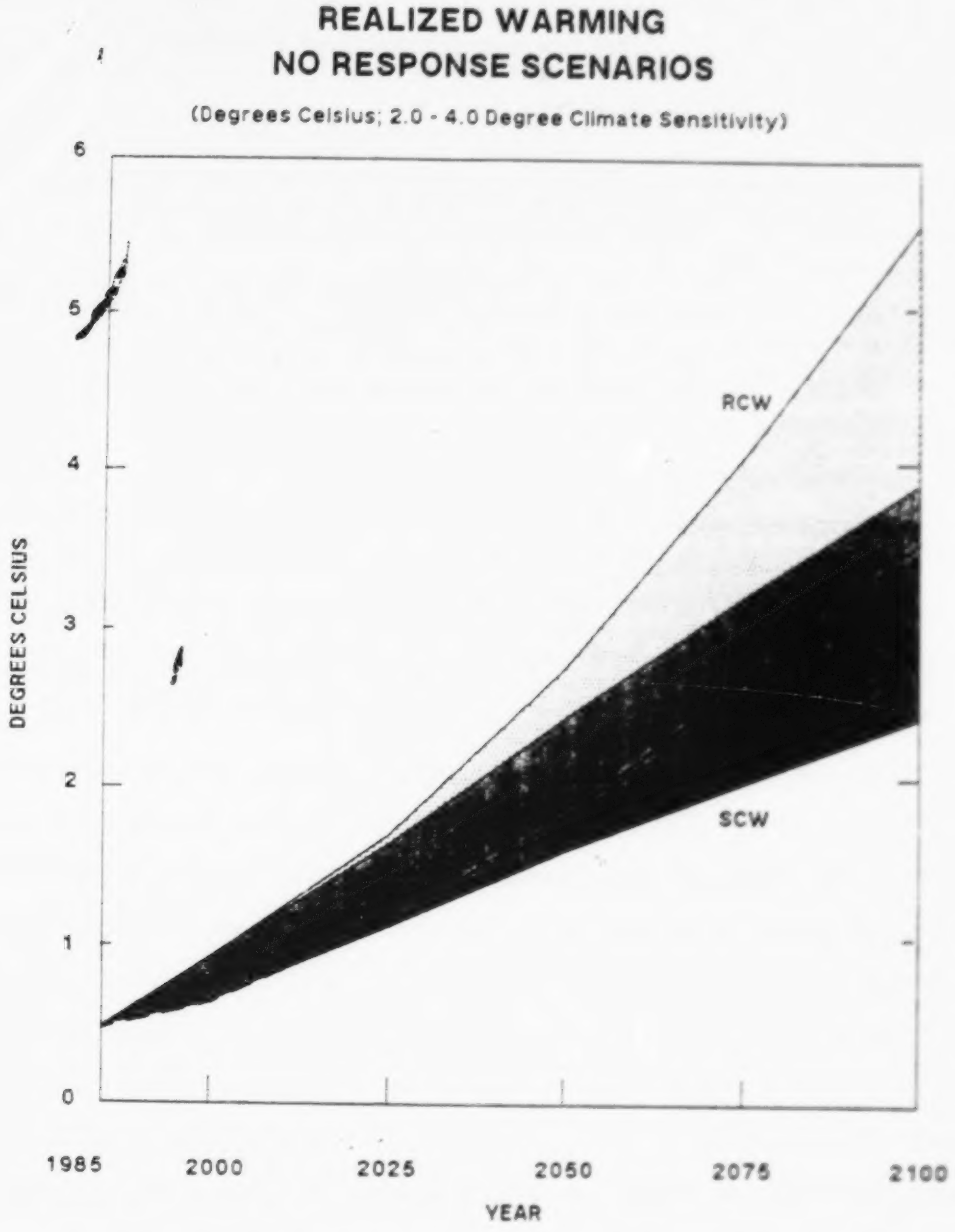


Figure 6. Shaded areas represent the range based on an equilibrium climate sensitivity to doubling CO_2 of 2-4°C.

BOX 2

Equilibrium and Realized Warming

Equilibrium Warming Commitment

The equilibrium warming commitment for any given year is the eventual increase in temperature that would occur at some point in the future if atmospheric concentrations of greenhouse gases were to remain constant at that year's levels.

Realized Warming

Because the oceans have a large heat capacity the temperature change realized in the atmosphere lags considerably behind the equilibrium level (the difference between the equilibrium warming and the realized warming in any given year is called the unrealized warming). Realized warming has been estimated with a simple model of ocean heat uptake.

Climate Sensitivity

Because the response of the climate system to changes in greenhouse gas concentrations is quite uncertain, we also consider a range of "climate sensitivities". Climate sensitivity is defined as the equilibrium warming commitment due to a doubling of the concentration of carbon dioxide from preindustrial levels. Given a particular emissions scenario and climate sensitivity, the realized warming is much more uncertain than the equilibrium warming commitment because the effective heat storage capacity of the ocean is not known. On the other hand, because the amount of unrealized warming increases with increasing climate sensitivity, for a given scenario, realized warming depends less on climate sensitivity than does equilibrium warming commitment.

and 2100. The total equilibrium warming commitment reaches 5-10°C by 2100.[1] In this case the maximum realized rate of change is 0.4-0.6°C per decade, which occurs sometime between 2070 and 2100.

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[1] Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

The Impact of Policy Choices

Government policies could significantly decrease or increase future warming. The warming suggested by the Slowly Changing and Rapidly Changing World cases is not inevitable; it is the result of the public and private choices implicit in these scenarios. While some future warming is locked in, there is a wide range of possibilities. It is prudent to begin to understand what impact alternative economic development strategies might have on future warming.

Scenarios with Stabilizing Policies

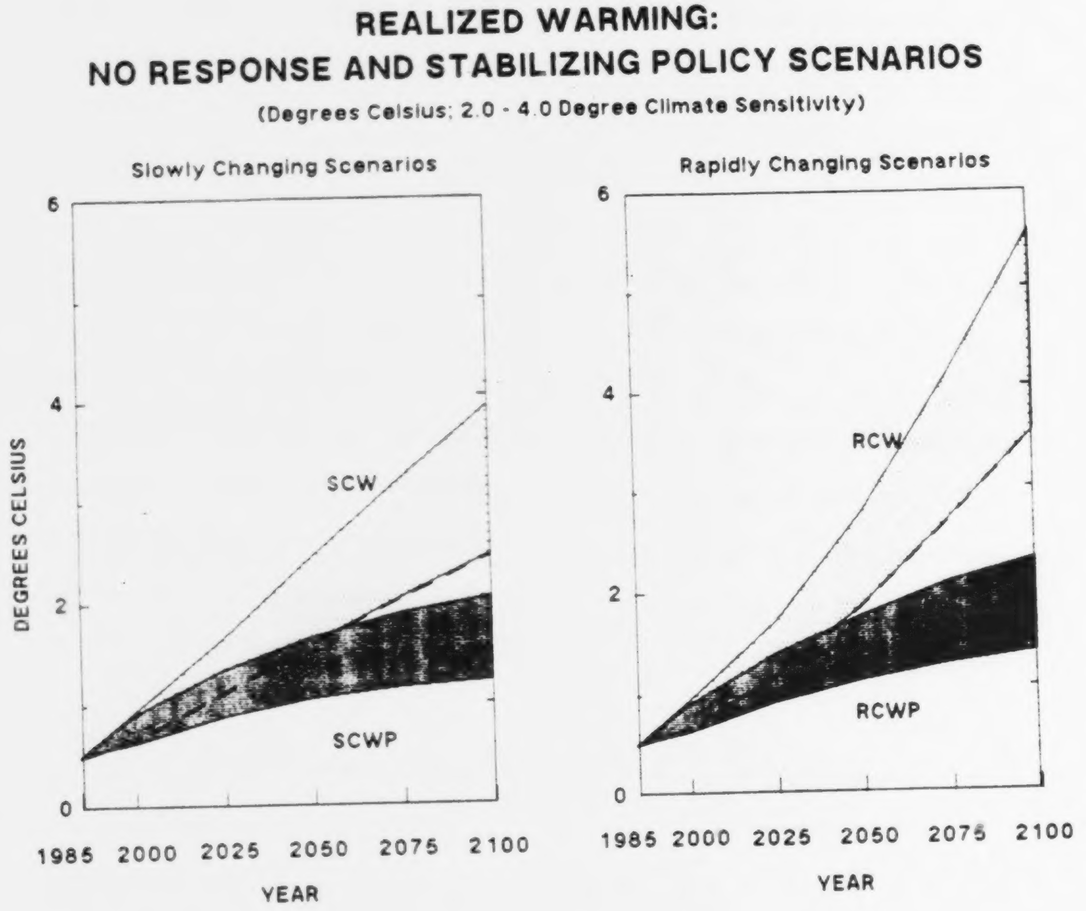
Two alternative scenarios were constructed to explore the impact of policy choices aimed at reducing the risk of global warming. These scenarios, labelled Slowly Changing World with Stabilizing Policies (SCWP) and Rapidly Changing World with Stabilizing Policies (RCWP) start with the same economic and demographic assumptions used in SCW and RCW scenarios, respectively, but assume that government leadership is provided to ensure that limiting greenhouse gas emissions becomes a consideration in investment decisions beginning in the 1990s. We assume that policies to promote energy efficiency in all sectors succeed in substantially reducing energy demand relative to the No Response scenarios (which already assume substantial efficiency improvements). We also assume that efforts to expand the use of natural gas increase its share of primary energy supply relative to other fossil fuels in the near term. Research and development investments in non-fossil energy supply options such as photovoltaics (solar cells) and biomass-derived fuels (fuels made from plant material) assure that these options are available and begin to become competitive after 2000. As a result, non-fossil energy sources meet a substantial fraction of total demand in later periods. The existing protocol to reduce CFC and halon emissions is assumed to be strengthened, leading to a phase-out of fully-halogenated compounds and a freeze on methyl chloroform. A global effort to reverse deforestation transforms the biosphere from a source to a sink for carbon by 2000, and technological innovation and controls reduce agricultural, industrial, and transportation emissions.

While the same general emissions reduction strategies are assumed in both the SCWP and RCWP cases, the degree and speed of improvement are higher in the RCWP scenario because technological innovation and capital stock replacement are greater in this case. The policies considered in these scenarios do not require changes in basic life styles. For example, energy use in buildings is greatly reduced in the Stabilizing Policy scenarios relative to the No Response scenarios, but the floor space available per person and the amenity levels provided are assumed to be the same. Similarly, the automobile efficiency assumptions are not inconsistent with the size distribution of the current vehicle fleet.

The impact of these policy assumptions is a substantial reduction in the rate of greenhouse gas buildup, but not a complete stabilization of the atmosphere (Figure 5). Carbon dioxide concentrations increase gradually throughout the time frame of the analysis despite declining emissions, reaching a level 65% greater than preindustrial values by 2100, or approximately one-third higher than current levels. Methane concentrations increase through about 2025, after which they level off and decline to roughly 1985 levels by 2100. Weighted CFC concentrations also increase rapidly at first, but they are relatively stable after about 2010. Nitrous oxide concentrations increase by an amount 40-50% less than the amount of increase in the RCW and SCW cases.

The calculated rate of climatic change in the Stabilizing Policy scenarios is between 0.6 and 1.4°C per century, or at least 60% less than in the corresponding worlds without a policy response to potential climatic change. Global temperatures in the SCWP case increase by 0.4-0.8°C from 2000 to 2050 and 0.6-1.1°C from 2000 to 2100; corresponding values are 0.5-0.9°C and 0.8-1.4°C in the RCWP case (Figure 7). Total equilibrium warming

FIGURE 7



REALIZED WARMING:
NO RESPONSE AND STABILIZING POLICY SCENARIOS

(Degrees Celsius; 2.0 - 4.0 Degree Climate Sensitivity)

Figure 7. Shaded areas represent the range based on an equilibrium climate sensitivity to doubling CO_2 of 2-4°C.

commitment reaches 1.4-2.8°C by 2100 in the SCWP case and 1.7-3.3°C in the RCWP case, assuming the climate sensitivity is 2-4°C. Given the possibility that the climate sensitivity could be higher and that there could be large positive biogeochemical feedbacks that are not included in these calculations, there is a possibility that even the Stabilizing Policy scenarios could lead to extremely high climatic change. It is also possible that the policies assumed in these scenarios could limit climatic change to about 1°C if the true climate sensitivity of the Earth is low.

If the risk of substantial climate change associated with the SCWP and RCWP scenarios is judged to be unacceptable, more aggressive policies will be required. Therefore we have constructed a Rapid Reduction case that examines the effect of measures that might be imposed to supplement those measures already analyzed in the RCWP scenario. This case implies that strategies that rapidly reduce greenhouse gas emissions are adopted beginning in 1990 (see below). In this scenario realized warming is limited to less than 2°C and the warming trend is reversed in the middle of the next century. All of the scenario estimates for realized and equilibrium warming are tabulated in Table 4 (including the results of an "Accelerated Emissions" scenario defined below).

The Relative Impact of Various Options On Future Warming

No single activity is the dominant source of greenhouse gases; therefore, no single measure can stabilize global climate. Many individual components, each having a modest impact on greenhouse gas emissions, can have a dramatic impact on the rate of climatic change when combined. This is illustrated in Figures 8 and 9, which show the impact of the key measures that account for the difference between the RCW, RCWP, and Rapid Reduction cases. To reduce the amount of global warming to the rates projected in the RCWP and Rapid Reduction cases, Table 5 lists several policies that might have to be adopted by 2000 to begin

TABLE 4

Scenario Results For Realized And Equilibrium Warming
(Degrees Centigrade)

Realized Warming - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.5°C	0.7°C	1.5°C	2.8°C	4.5°C	>6°C[*]
RCW	0.5	0.7	1.2	1.9	2.7	3.6
SCW	0.5	0.7	1.1	1.6	2.0	2.5
RCWP	0.5	0.6	0.9	1.1	1.3	1.4
SCWP	0.5	0.6	0.9	1.0	1.2	1.2
Rapid Reduction	0.5	0.6	0.8	0.8	0.8	0.7

Realized Warming - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.5	1.0	2.1	4.1	>6	>6
RCW	0.5	0.9	1.7	2.8	4.1	5.6
SCW	0.5	0.9	1.7	2.5	3.2	4.0
RCWP	0.5	0.9	1.4	1.8	2.1	2.3
SCWP	0.5	0.9	1.3	1.7	1.9	2.0
Rapid Reduction	0.5	0.9	1.3	1.4	1.3	1.2

Equilibrium Warming Commitment - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.7	1.1	2.4	4.3	>6	>6
RCW	0.7	1.1	1.7	2.7	3.8	4.8
SCW	0.7	1.0	1.6	2.2	2.7	3.1
RCWP	0.7	1.0	1.3	1.5	1.6	1.7
SCWP	0.7	1.0	1.2	1.3	1.4	1.4
Rapid Reduction	0.7	1.0	1.1	1.0	.9	.7

Equilibrium Warming Commitment - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	1.5	2.2	4.7	>6	>6	>6
RCW	1.5	2.1	3.5	5.4	>6	>6
SCW	1.5	2.1	3.3	4.5	5.4	>6
RCWP	1.5	2.0	2.5	2.9	3.2	3.3
SCWP	1.5	1.9	2.4	2.7	2.8	2.8
Rapid Reduction	1.5	1.9	2.1	2.0	1.7	1.3

[*] Estimates of warming greater than 6°C represent extrapolations beyond the range tested in most climate models.

STABILIZING POLICY STRATEGIES:
DECREASE IN EQUILIBRIUM WARMING COMMITMENT

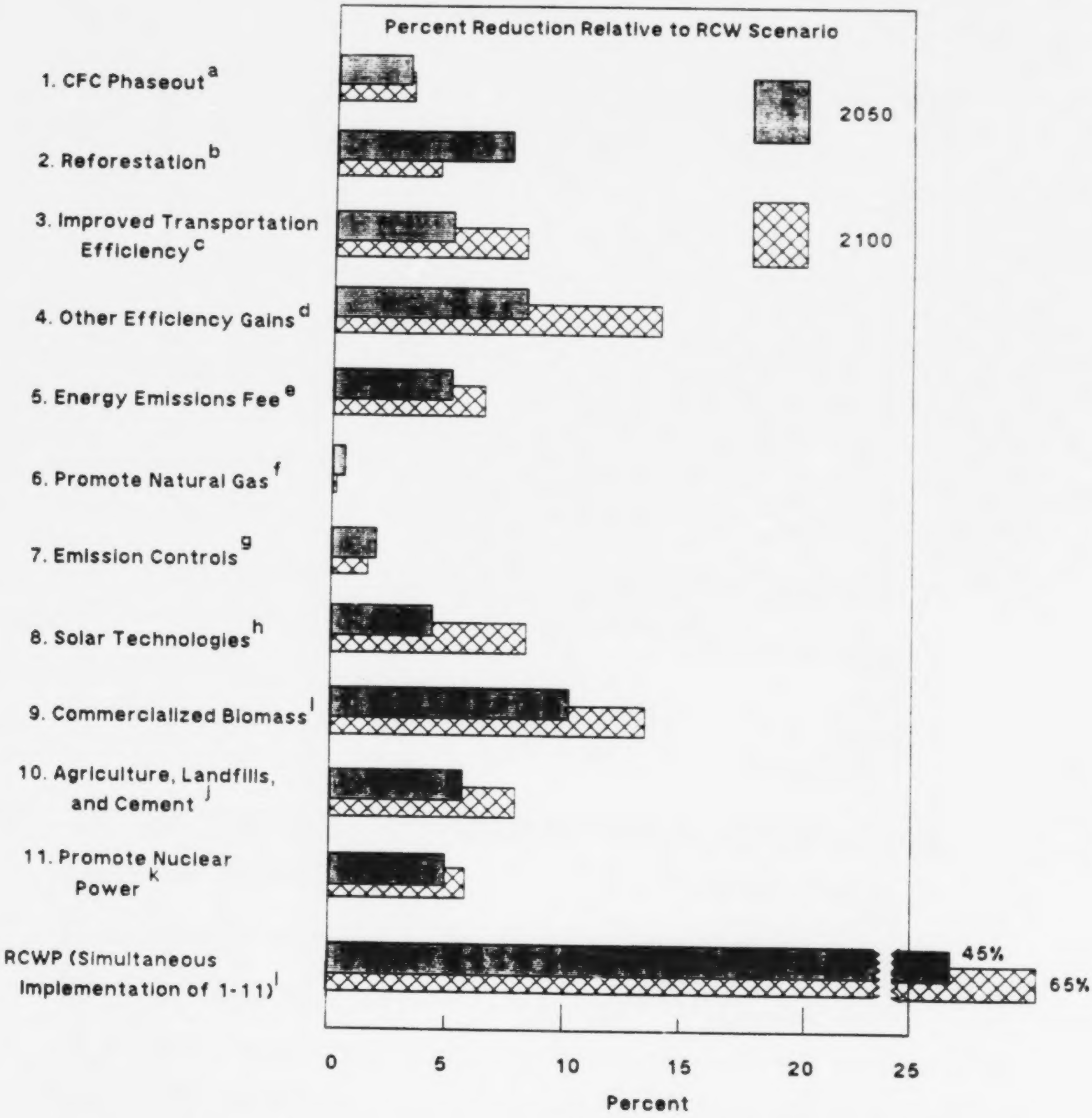


Figure 8. The impact of individual measures on the equilibrium warming commitment in the RCW scenario. The simultaneous implementation of all the measures represents the RCWP scenario.

FIGURE 8 -- NOTES

Impact Of Stabilizing Policies On Global Warming

[a] A 100% phaseout of CFCs by 2003 and a freeze on methyl chloroform is imposed. There is 100% participation by industrialized countries and 94% participation in developing countries.

[b] The terrestrial biosphere becomes a net sink for carbon by 2000 through a rapid reduction in deforestation and a linear increase in the area of reforested land and biomass plantations. Net CO_2 uptake by 2025 is 0.7 Pg C per year.

[c] The average efficiency of new cars in the U.S. reaches 40 mpg (5.9 liters/100 km) by 2000. Global fleet-average automobile efficiency reaches 50 mpg by 2025 (4.7 liters/100 km).

[d] The rate of energy efficiency improvements in the residential, commercial, and industrial sectors are increased about 0.1-0.2 percentage points by 2025 compared to the RCW, and about 0.3-0.4 percentage points annually from 2025-2100.

[e] Emission fees are placed on fossil fuels in proportion to carbon content. Maximum production fees (1985$) were $0.50/GJ for coal, $0.36/GJ for oil, and $0.23/GJ for natural gas. Maximum consumption fees were 28% for coal, 20% for oil, and 13% for natural gas. These fees increased linearly from zero, with maximum consumption fees charged by 2025 and maximum production fees charged by 2050.

[f] Assumes that economic incentives accelerate exploration and production of natural gas, reducing the cost of locating and producing natural gas by an annual rate of .5% relative to the RCW scenario. Incentives for gas use for electricity generation increases gas share by 5% in 2025 and 10% thereafter.

[g] Assumes more stringent NO_x and CO controls on mobile and stationary sources including all gas vehicles using three-way catalysts in OECD countries by 2000 and in the rest of the world by 2025 (new light duty vehicles in the rest of the world uses oxidation catalysts from 2000 to 2025); from 2000 to 2025 conventional coal boilers used for electricity generation are retrofit with low NO_x burners, with 85% retrofit in the developed countries and 40% in developing countries; starting in 2000 all new combustors used for electricity generation and all new industrial boilers require selective catalytic reduction in the developed countries and low NO_x burners in the developing countries, and after 2025 all new combustors of these types require selective catalytic reduction; other new industrial non-boiler combustors such as Kilns and Dryers require low NO_x burners after 2000.

[h] Assumes that low-cost solar technology is available by 2025 for as little as 4.6 cents/kwh.

[i] Assumes the cost of producing and converting biomass to modern fuels reaches $4.00/gigajoule (1985$) for gas and $6.00/gigajoule (1985$) for liquids. The maximum amount of liquid or gaseous fuel available from biomass is 210 exajoules.

[j] Assumes that research and improved agricultural practices result in an annual decline of 0.5% in the emissions from rice production, enteric fermentation, and fertilizer use. CH_4 emissions from landfills are assumed to decline at an annual rate of 2% in developed countries due to policies aimed at reducing waste and landfill gas recovery; emissions in developing countries continue to grow until 2025 then remain flat due to incorporation of the source policies. Technological improvements reduce demand for cement by 25%.

FIGURE 8 -- NOTES (Continued)

Impact Of Stabilizing Policies On Global Warming

[k] Assumes that the cost of nuclear technology declines by 0.5% per year.

[l] Impact on warming when all the above measures are implemented simultaneously. The sum of each individual reduction in warming is not precisely equal to the difference between the RCW and RCWP cases because not all the strategies are strictly additive.

RAPID REDUCTION STRATEGIES:
ADDITIONAL DECREASE IN EQUILIBRIUM WARMING COMMITMENT

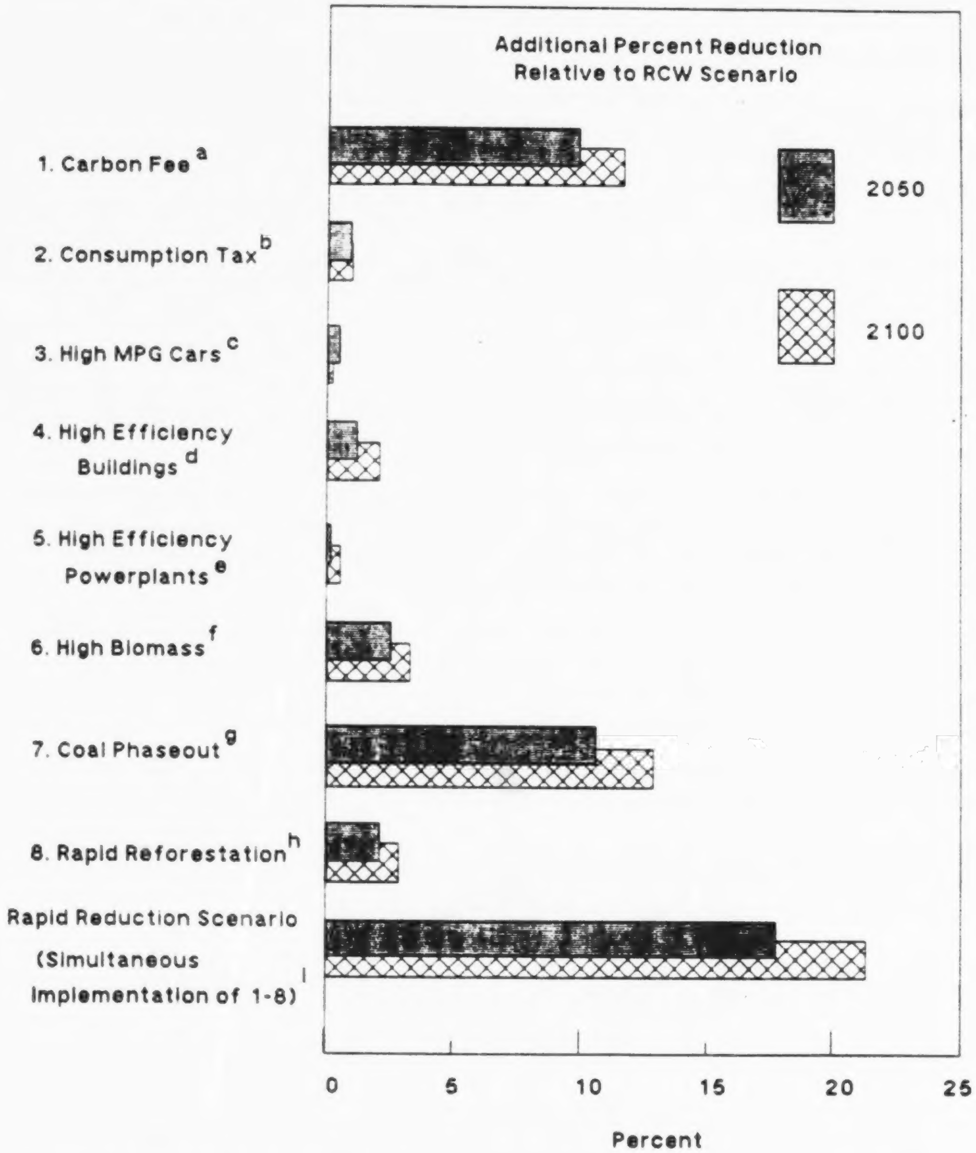


Figure 9. The impact of additional measures applied to the RCWP scenario expressed as percent change relative to the equilibrium warming commitment in the RCW scenario. The simultaneous implementation of all the measures in combination with the measures in the RCWP scenarios represents the Rapid Reduction scenario.

FIGURE 9 -- NOTES

Impact Of Rapid Reduction Policies On Global Warming

[a] High carbon emissions fees are imposed on the production of fossil fuels in proportion to the CO_2 emissions potential. In this case, fees of $8.50/GJ were imposed on unconventional oil production, $5.70/GJ on coal, $2.30/GJ on oil, and $1.10/GJ on natural gas. These fee levels are specified in 1985$ and are phased in over the period between 1985 and 2050.

[b] A percentage excise tax, proportional to the carbon content of the fuel, was levied on fuel use. Consumption taxes were also imposed in the RCWP case. In this case, the tax on coal consumption was increased from 28% of the price to 40%; the tax on oil use was increased from 20% to 30%; the tax on natural gas use was increased from 13% to 20%; the tax on electricity use was increased from 0 to 5%. These taxes were phased in and fully applied by 2025.

[c] Assumes that the average efficiency of new cars in the U.S. reaches 50 mpg (4.7 liters/100 km) in 2000 and that global fleet-average auto efficiencies reach 65 mpg in 2025 (3.6 liters/100 km) and 100 mpg (2.4 liters/100 km) in 2050.

[d] Assumes that the rate of technical efficiency improvement in the residential and commercial sectors improves substantially beyond that assumed in the RCWP case. In this case, the rate of efficiency improvement in the residential and commercial sectors is increased so that a net gain in efficiency of 50% relative to the RCWP case is achieved in all regions.

[e] Assumes that, by 2050, average power plant conversion efficiency improves by 50% relative to the RCWP case. In this scenario the design efficiencies of all types of generating plants improve significantly. For example, by 2025, oil-fired generating stations achieve an average conversion efficiency roughly equivalent to that achieved by combined-cycle units today.

[f] The availability of commercial biomass was doubled relative to the assumptions in the RCWP case. In this case the rate of increase in biomass productivity is assumed to be at the high end of the range suggested by the U.S. DOE Biofuels Program. Conversion costs were assumed to fall by half relative to the assumptions in the RCWP case.

[g] Environmental fees of about $20/GJ (in 1985$) are phased in by 2050. This has the effect of gradually making coal uncompetitive in utility markets.

[h] A rapid rate of global reforestation is assumed. In this case deforestation is halted by 2000 and the biota become a net sink for CO_2 at a rate of about 1 Pg C per year by 2025, about twice the level of carbon storage assumed in the RCWP case.

[i] Impact on warming when all of the above measures are implemented simultaneously. The impact is much less than the sum of the individual components because many of the measures are not additive.

TABLE 5

Examples Of Policy Responses By The Year 2000

RCWP Case

- New automobiles in the U.S. average 40 mpg
- New automobiles in the OECD use 3-way catalytic converters to reduce CO and NO_x (current U.S. standard); rest of world uses an oxidation catalyst
- Average space heating requirements of new single family homes are 50% below 1980 new home average
- Net global deforestation stops
- CFCs are phased out; production of methyl chloroform is frozen
- Emission fees are placed on fossil fuels in proportion to carbon content--$2.50/ton on coal, $0.50/barrel on oil, $0.05/thousand cubic feet on natural gas
- Research and development into solar photovoltaic technology allows solar to compete with oil and natural gas (DOE long-term policy goals)
- Available municipal solid waste and agricultural wastes are converted to useful energy
- Biomass energy plantations increase current productivity by 65% (to 25 dry tons/hectare annually)

Rapid Reduction Case

- New automobiles in the U.S. average 50 mpg
- Major retrofit initiatives reduce energy use in existing commercial buildings by 40%
- Average space heating requirements of new single family homes are 90% below 1980 new home average
- Global deforestation stops; Major reforestation programs undertaken
- CFCs are phased out; production of methyl chloroform is frozen
- Emission fees are placed on fossil fuels in proportion to carbon content--$29/ton on coal, $3.25/barrel on oil, $0.25/thousand cubic feet on natural gas
- Commercialization incentives lead to significant market penetration for solar technologies
- 250 million hectares globally are committed to biomass energy plantations, i.e., 5% of forest and woodland area

reducing greenhouse gas emissions. These policies are meant to illustrate potential policy responses; a variety of policy combinations might achieve the reductions in global warming estimated in each case.

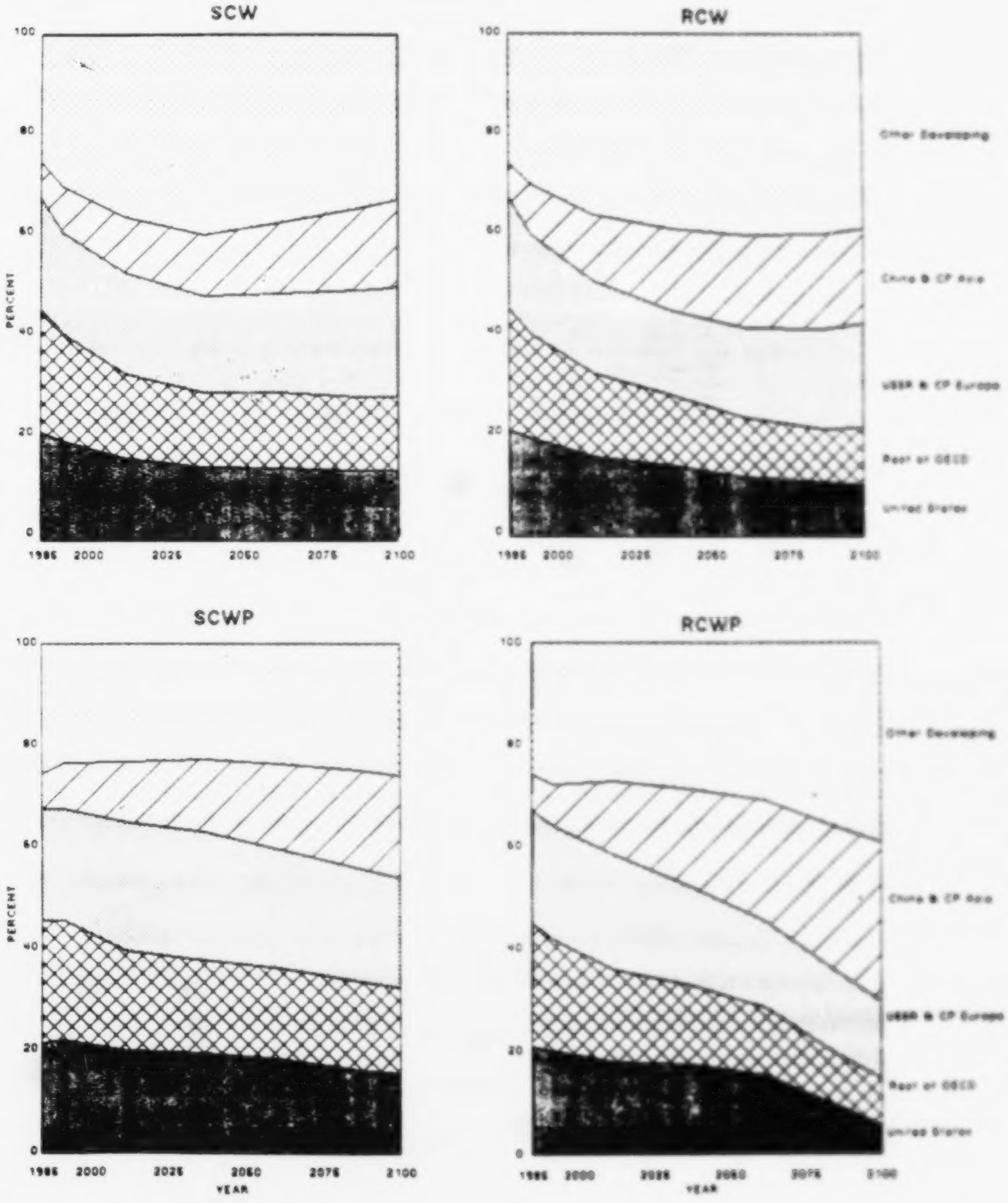
This analysis suggests that accelerated energy efficiency improvements, reforestation, modernization of biomass use, and carbon emissions fees could have the largest impact on the rate of climatic change over the next few decades. In the long run, advances in solar technology and biomass plantations also play an essential role. The measures that reduce the warming to the greatest extent in the Rapid Reduction case relative to the RCWP case are those that change the fuel mix. For example, imposing stiff carbon fees on the production of fossil fuels, and increasing the assumed level of biomass availability. Table 4 indicates that only the most aggressive policy case ensures that the rate of warming will be below a tenth of a degree Celsius per decade. This is still about twice the average rate of warming experienced over the last century.

Because of the large potential for growth in their emissions, the participation of developing countries is crucial for stabilizing greenhouse gases. Increasing the availability of energy services is a high priority for developing countries attempting to meet basic human needs. Increased energy use in developing countries could lead to dramatic increases in greenhouse gas emissions unless stabilizing policies are adopted. The share of greenhouse gas emissions arising from developing countries (weighted by their estimated impact on global warming) increases from about 40% currently to 50% by 2025 and almost 60% by 2100 in the RCW scenario; the developing countries' contributions in greenhouse gas emissions also rise to about 50% in the SCW (Figure 10). We examined the implications for global warming if industrialized countries adopted climate stabilizing policies without the participation of developing countries. Stabilizing policies adopted by industrialized countries, however, are likely to affect the development path of other countries even if these other countries do not explicitly adopt such policies. Therefore, we assumed that technological diffusion

FIGURE 10

SHARE OF GREENHOUSE GAS EMISSIONS BY REGION

(Percent)



would result in energy efficiency improvements in developing countries at a rate between the rates assumed in the No Response and Stabilizing Policy cases. Some other factors, such as when the cost of solar energy becomes competitive in developing countries, were also assumed to be between the assumptions in these two scenarios. With these assumptions, equilibrium warming commitment in 2050 is about 40% higher compared to the scenarios with global cooperation (Figure 11). This implies that action by industrialized countries on their own can significantly slow the rate and magnitude of climate change, but that without the participation of the developing countries, the risk of substantial global warming remains.

Delaying the policy response to the greenhouse gas buildup would substantially increase the global commitment to future warming. The Stabilizing Policy cases and the Rapid Reduction case both assume that starting in 1990 action is taken to begin reducing the rate of greenhouse gas buildup, and that significant policies are in force by 2000. It has been suggested that any response should be delayed until the current level of scientific uncertainty is substantially reduced. The impact of such a course was investigated by assuming that industrialized countries delay action until 2010 and that developing countries delay action until 2025. Once action is initiated, policies are assumed to be implemented at roughly the same rate as in the Stabilizing Policy cases. The result is a significant increase in global warming (Figure 12): The equilibrium warming commitment in 2050 increases by about 40% compared to the scenarios with policy implementation beginning in 1990.

Government policies could also significantly exacerbate climate change. Decisions that will be made in the near future may lead to increased emissions if there is no clear policy goal to reduce them. This possibility is illustrated by a set of tests that were conducted starting with the RCW scenario. In this "Accelerated Emissions" case, several key parameters were varied as proxies

FIGURE 11

INCREASE IN REALIZED WARMING
WHEN DEVELOPING COUNTRIES DO NOT PARTICIPATE

(Degrees Celsius; Based on 3.0 Degree Sensitivity)

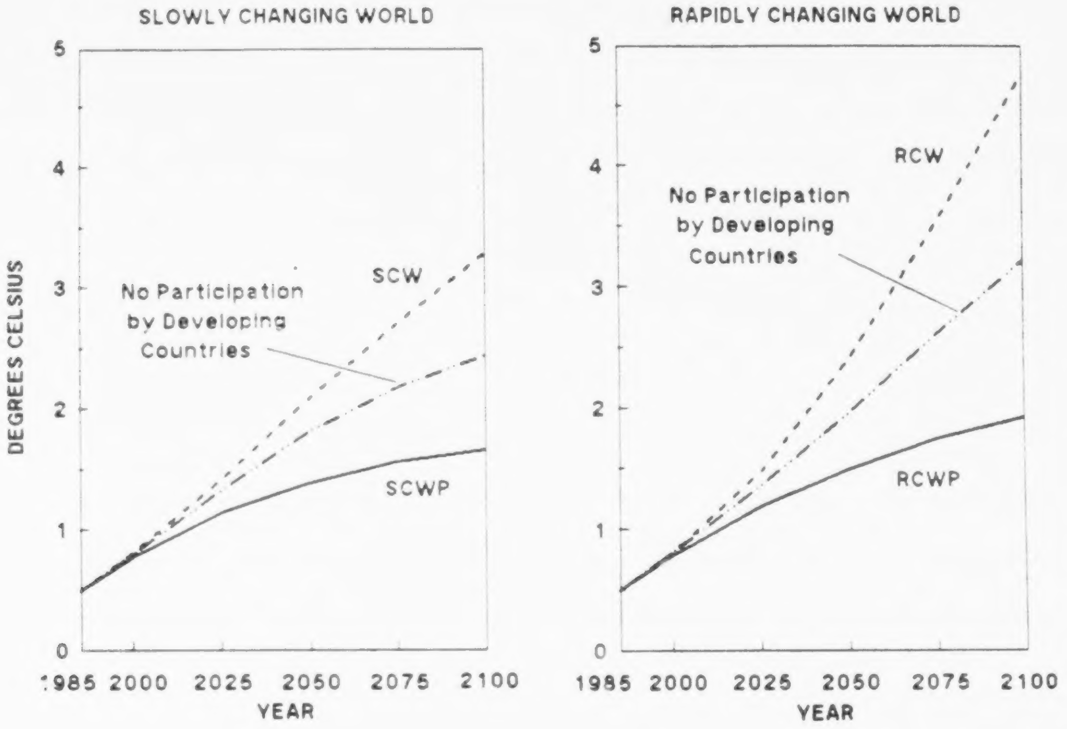
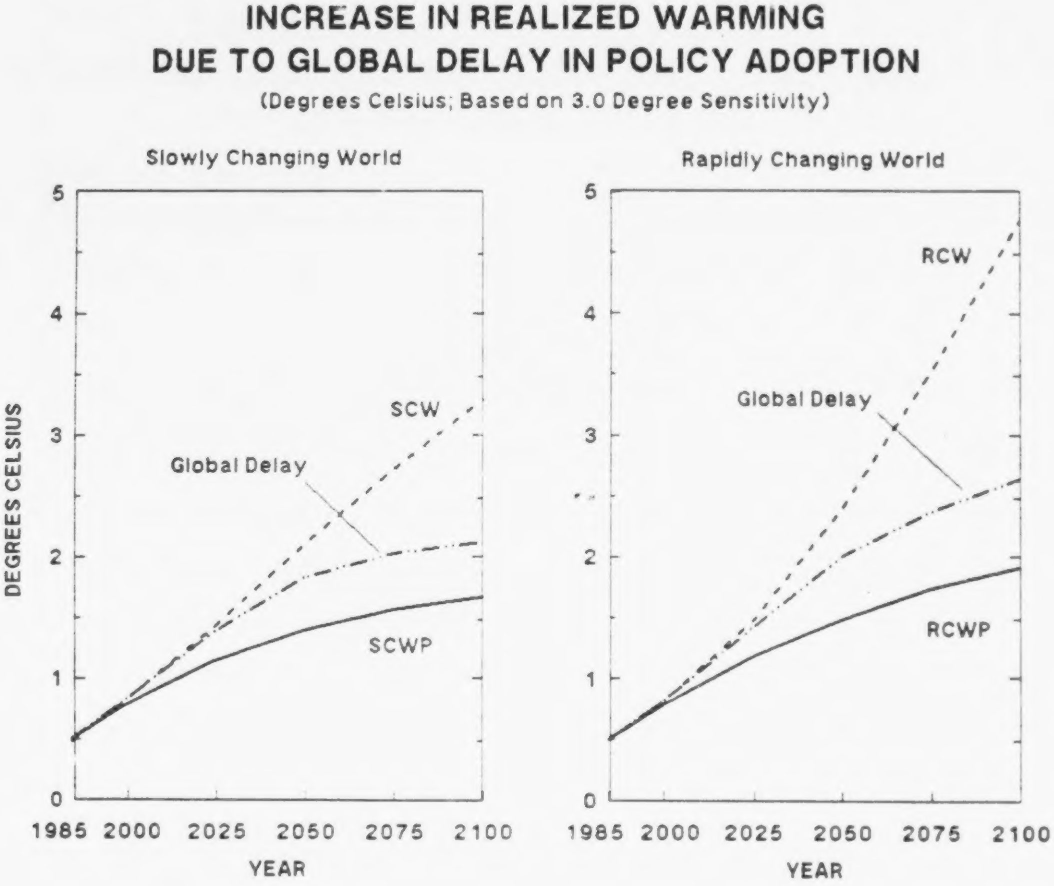


Figure 11. Assumes that industrialized countries follow the RCW scenario while developing countries follow the RCWP, except that there is some transfer of low-emissions technology to developing countries despite their failure to adopt stabilizing policies.

FIGURE 12



INCREASE IN REALIZED WARMING DUE TO GLOBAL DELAY IN POLICY ADOPTION

(Degrees Celsius; Based on 3.0 Degree Sensitivity)

Figure 12. Assumes that industrialized countries delay action until 2010 and that developing countries delay action until 2025. Once action is initiated, policies are assumed to be implemented at roughly the same rate as in the Stabilizing Policy cases.

for currently proposed policies (e.g., accelerated development of synfuels) or the possible consequences of government inaction or failure (e.g., high use of CFCs and deforestation).

Figure 13 summarizes the results of these tests as compared with the RCW scenario. The results are illustrated in terms of the incremental effect of each policy outcome on the equilibrium warming commitment in 2050 and 2100. Figure 13 indicates that the measures that amplify the warming to the greatest extent are those that reduce the rate of efficiency improvement, reduce the cost of synfuels, and increase the assumed rate of growth in CFC production and use. Policies leading to accelerated deforestation would have a large impact in the near term, but a relatively small impact on the result in 2100. The impact of all of these policies in combination could be to increase the equilibrium warming commitment in 2050 by 60% compared with the RCW scenario.

Sensitivity of Results to Alternative Assumptions

Many factors could increase or decrease future warming. The specific estimates of climatic change presented above are subject to a variety of uncertainties involving technological and economic assumptions as well as the response of the Earth-atmosphere system to perturbations.

Many uncertainties regarding the response of the climate system, such as the role of clouds and sea ice changes, can be reflected by varying the climate sensitivity parameter. The results presented above were based on a central estimate of 2-4°C for the equilibrium warming from a doubling of the concentration of carbon dioxide. Broadening this range to 1.5-5.5°C has one of the largest impacts on estimates of future warming (Figure 14). In the RCW scenario the range of realized warming in 2050 increases from 1.9-2.8°C to 1.5-3.2°C; the impact on equilibrium warming is much greater, increasing the range of the commitment estimated in 2050 from 2.7-5.4°C to 2.0-7.4°C.

FIGURE 13

ACCELERATED EMISSIONS CASES: PERCENT INCREASE IN EQUILIBRIUM WARMING COMMITMENT

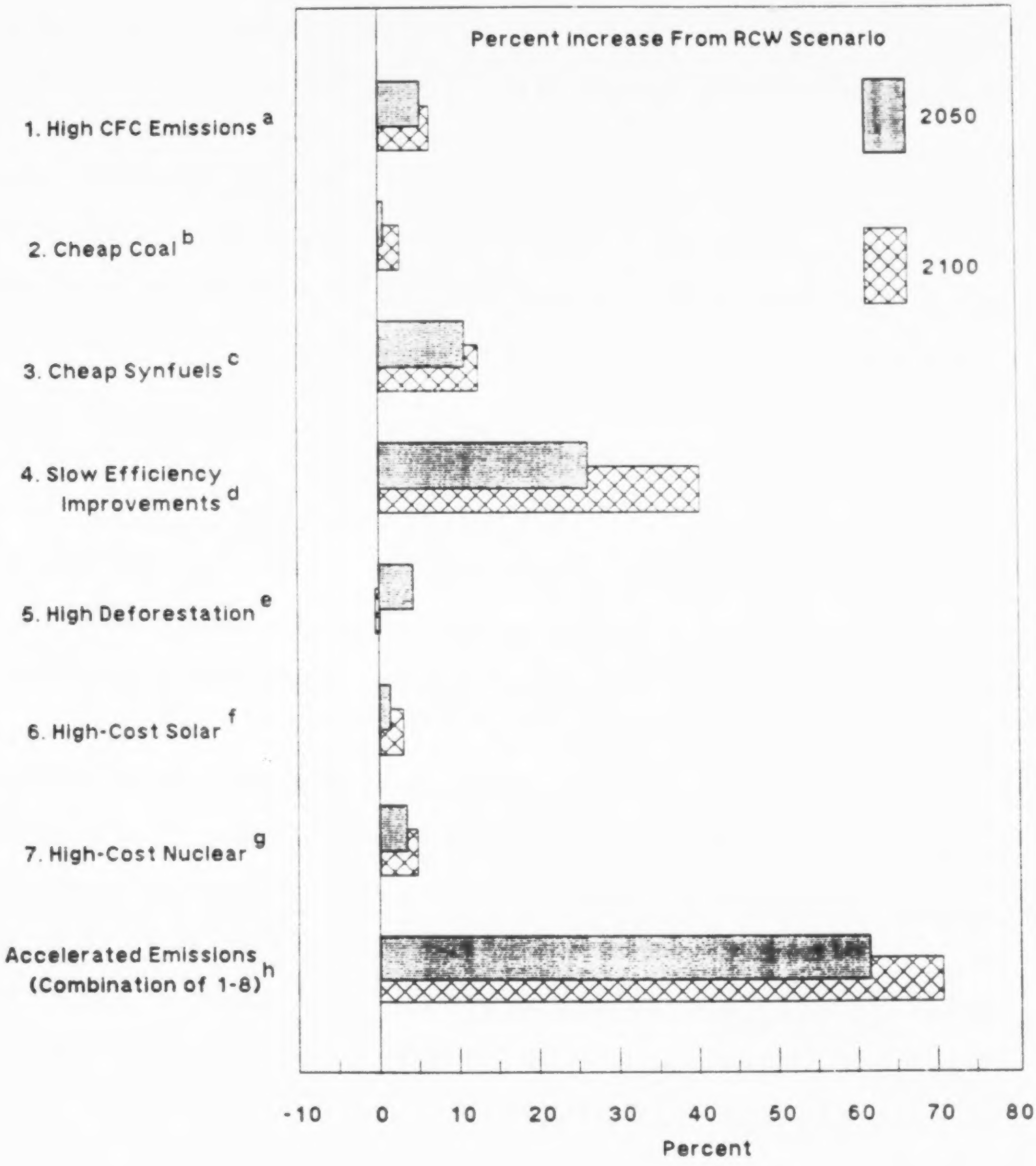


FIGURE 13 -- NOTES

Impact Of Accelerated Emissions Policies On Global Warming

[a] Assumes a low level of participation in and compliance with the Montreal Protocol. The assumptions used in this case are similar to those used in the "Low Case" analysis described in the EPA's Regulatory Impact Assessment report.

[b] Assumes that advances in the technology of coal extraction and transport rapidly reduce the market price of coal at the burner tip. In the RCW scenario, the economic efficiency of coal supply is assumed to improve at a rate of approximately 0.5% per year. In this case, it is assumed to improve at a rate of 1% per year.

[c] Assumes that the price of synthetic oil and gas could be reduced by 50% and commercialization rapidly accelerated relative to the RCW case. This case assumes that the minimal production price for synfuels can be achieved in 20 years rather than the 30 years assumed in the RCW case.

[d] Assumes that technical gains in the engineering efficiency of energy use occurs only half as rapidly as assumed in the RCW case. In the RCW case it is assumed that efficiency improves at rates of approximately 1-2% per year. In the Slow Improvement case the assumed rates were reduced to only 0.5-1.0% per year. The lower rate of improvement is similar to the assumptions in recent projections for the Department of Energy's National Energy Policy Plan.

[e] Assumes annual deforestation increases at a rate equal to the rate of growth in population.

[f] Assumes that solar energy remains so expensive that the possibility of its making any significant contribution to global energy supply is precluded.

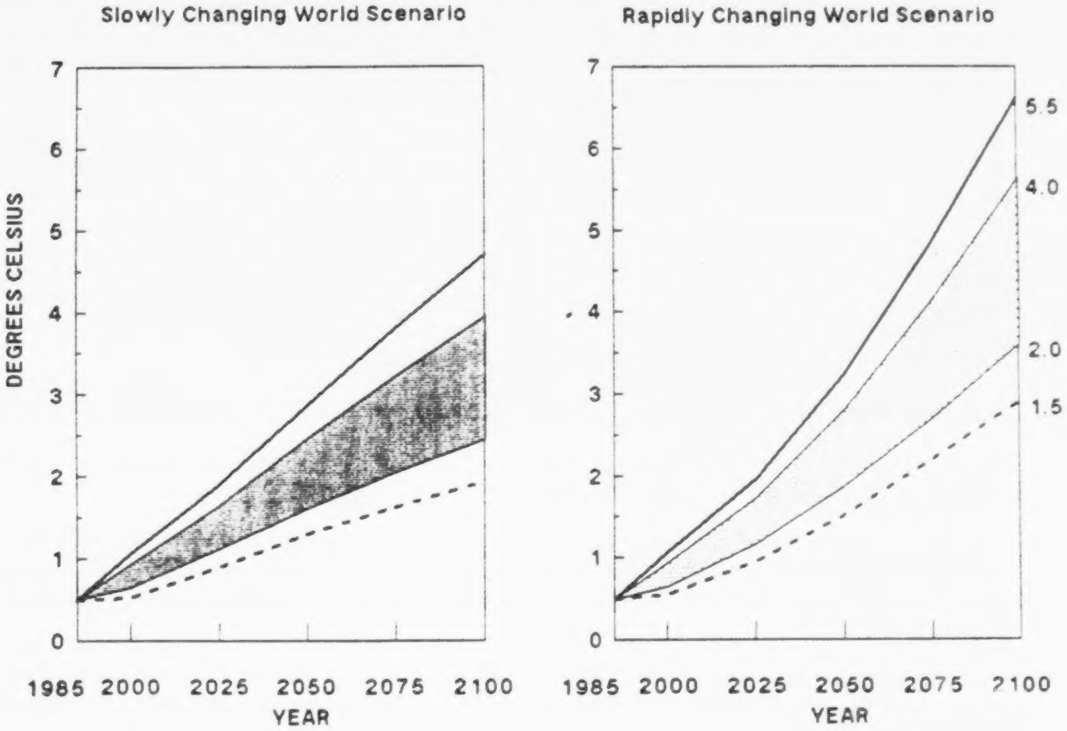
[g] Assumes that the cost of electricity from fission electric systems becomes so high that their contribution to global energy supply is permanently limited. In this case, an environmental tax of about $40 (1985$) per gigajoule (GJ) on the price of electricity supplied by nuclear power plants was phased in by 2050.

[h] All of the above assumptions were combined in one scenario. The result is not equal to the sum of the warming in the RCW and the eight individual cases because of interactions among the assumptions.

FIGURE 14

IMPACT OF CLIMATE SENSITIVITY ON REALIZED WARMING

(Degrees Celsius; 1.5-5.5 Degree Climate Sensitivity)



There is a similar impact on warming estimates in the SCW. The sensitivity of the results from the RCW scenario to a wide range of other assumptions has been tested; the results are summarized in Table 6.

A variety of factors related to technology, resources, and emissions factors could significantly influence the projected warming. Of these factors, the largest impacts are due to assumptions that affect the relative price of coal and non-fossil fuels in the future. If, in the absence of policies, non-fossil technology decreased in price much faster than we assumed in the RCW, or coal prices increased much faster than we assumed in the RCW, then warming in 2100 could be as much as one-fourth lower than calculated for this scenario. The impact of increasing the assumed availability of oil and gas was surprisingly low. Larger supplies led to greater total demand and reductions in the share of energy supplied by coal and non-fossil fuels; these factors in combination left greenhouse gas emissions and estimated warming almost unchanged. Had the assumed increase in gas availability been coupled with policies intended to encourage its use as a transition fuel to a non-fossil world, then a much larger impact may have been seen. Current sources of methane and nitrous oxide are quite uncertain, but these uncertainties appear to have only a modest impact on projected warming: up to 5% in the case of methane.

The oceans and biosphere play a major and highly uncertain role in the climate system. Their ability to absorb CO_2 and heat is a key determinant of the rate and magnitude of climatic change (Table 6). Alternative formulations of carbon dioxide absorption by the ocean and any other carbon sinks have a significant impact on estimated climatic change. A variety of ocean models with very different structure produced similar estimates of future carbon dioxide concentrations, with the exception of the outcrop (Siegenthaler) model, which calculated lower concentrations in 2100; if this model were correct, the equilibrium warming commitment in 2100

TABLE 6

Sensitivity Analysis: Impact on Realized Warming and Equilibrium Warming (Percent change from RCW scenario)[a]

Sensitivity Case Assumptions	2050 Realized	2050 Equilibrium	2100 Realized	2100 Equilibrium
TECHNOLOGY, RESOURCES, AND EMISSION FACTORS				
Low Cost Non-Fossil Technology[b]	-6 to -13%	-9 to -17%	-16 to -25%	-19 to -26%
Fossil Resources				
High Coal Price[c]	-10	-14	-23	-26
High Oil Supply[d]	<1	<-1 to 1	-1	-2
High Gas Supply[e]	1	1	<1	<1
Alternative Starting Methane Budgets[f]	-3 to 4	-3 to 5	-3 to 5	-3 to 5
N_2O From Fertilizer				
High Emissions From Anhydrous Ammonia[g]	0	0	0	0
High Emissions From Fertilizer Leaching[h]	0 to -0.1	0 to -0.1	0	0
High N_2O From Combustion[i]	-0.1 to 0	0 to 0.1	0	0
High Initial Biomass On Cleared Land[j]	2	2	1	1
OCEAN CO_2 AND HEAT UPTAKE				
Alternative CO_2 Models[k]				
Oeschger et al.[l]	-	-3	-	-4
Bolin et al.[m]	-	-3	-	-4
Bjorkstrom[n]	-	-3	-	-4
Siegenthaler[o]	-	-3	-	-12

TABLE 6 (continued)

Sensitivity Analysis: Impact on Realized Warming and Equilibrium Warming (Percent change from RCW scenario)[a]

Sensitivity Case Assumptions	2050 Realized	2050 Equilibrium	2100 Realized	2100 Equilibrium
Alternative Unknown Sink Assumptions[p]	-7 to 3	-8 to 3	-13 to 3	-14 to 3
Heat Diffusion Rate[q]				
2°C Sensitivity	-17 to 11	0	-14 to 9	0
4°C Sensitivity	-23 to 17	0	-21 to 16	0
ATMOSPHERIC CHEMISTRY MODEL ASSUMPTIONS				
CFC-11 Lifetime[r]	-0.1 to 0.1	-0.1 to 0.1	-0.1 to 0.1	-0.1 to 0.1
Chlorine/Col O_3 Parameter[s]	-4	-6	-8	-8
Trop O_3/CH_4 Parameter[t]	1	1	1	1
OH/NO_x Parameter[u]	-1 to 1	-2 to 1	-2 to 1	-2 to 1
FEEDBACKS				
Ocean Circulation Surprise[v]				
2°C Sensitivity	0	0	35	4
4°C Sensitivity	49	4	62	11
CH_4 Hydrate and Wetland Emissions[w]				
2°C Sensitivity	10	11	12	12
4°C Sensitivity	15	16	18	19
Ocean Mixing, CH_4 Emissions, Terrestrial Biota[x]				
2°C Sensitivity	19	14	22	15
4°C Sensitivity	33	31	43	33

TABLE 6 -- NOTES

[a] The percent changes are independent of the assumed climate sensitivity except where noted.

[b] These ranges represent modest to optimistic assumptions about future commercial availability of non-fossil technologies, e.g., solar photovoltaics, advanced nuclear power designs, and synthetic fuel production from biomass. Solar photovoltaic costs decline to 4.6 cents/kwh (1985$) by 2020 in the optimistic scenario and by 2050 in the modest assumptions. Nuclear costs decline at an annual rate of 0.5% in the optimistic assumptions and remain relatively flat in the modest assumptions compared to an overall growth of 1.5 cents/kwh assumed in the RCW scenario. Assumes that the cost of producing and converting biomass to modern fuels reaches $4.00/gigajoule for gas and $6.00 (gigajoule) for liquids by 2020 in the optimistic assumptions and by 2050 in the modest assumptions. The total amount of fuel available from biomass is 210 exajoules.

[c] The impact of an escalation in coal prices above the RCW case by about 1% annually from 1985 to 2100.

[d] The impact of an increase in global oil resources to 25,000 exajoules, more than double the estimate in the RCW case, assuming proportionate increases in resource availability at each cost level.

[e] The impact of an increase in global natural gas resources to 27,000 exajoules, more than 2.5 times the estimate in the RCW case, assuming proportionate increases in resource availability at each cost level.

[f] These ranges represent assumptions about the relative sizes of anthropogenic versus non-anthropogenic sources of methane emissions thereby affecting growth in emissions over time, i.e., high emission levels (373 Tg CH_4) from anthropogenic activities such as fuel production and landfilling with low emission levels (137 Tg CH_4) from natural processes such as oceans and wetlands, versus low anthropogenic emissions (245 Tg CH_4) with high natural emissions (265 Tg CH_4).

[g] The impact of elevating the emission coefficient for the anhydrous ammonia fertilizer type (the percent of N evolved as N_2O) from 0.5% to 2.0%.

[h] The impact of assuming additional N_2O emissions from fertilizer leaching into surface water and ground water, modeled by increasing all the fertilizer emission coefficients by 1 percentage point.

[i] The impact of higher emission coefficients for N_2O from combustion; assumes that N_2O emissions are about 25% of NO_x emissions, thus the N_2O emissions from combustion sources in 1985 equaled 2.3 Tg N, over two times the level assumed in the RCW case.

[j] The impact of assuming a higher estimate for the amount of carbon initially contained in forest vegetation and soils (roughly a 50-100% increase) and a more rapid rate of change in land use, resulting in carbon emissions of 281 Pg from 1980 to 2100 compared with 188 Pg C in the RCW scenario.

[k] Realized warming was not calculated in these tests.

[l] This box-diffusion model represents the turnover of carbon below 75 meters as a purely diffusive process.

TABLE 6 – NOTES (continued)

[m] This is a 12-compartment regional model which divides the Atlantic and Pacific-Indian Oceans into surface-, intermediate-, deep-, and bottom-water compartments and divides the Arctic and Antarctic Oceans into surface- and deep-water compartments.

[n] This is an advective-diffusive model that divides the ocean into cold and warm compartments; water downwells directly from the cold surface compartment into intermediate and deep layers.

[o] An outcrop-diffusion model that allows direct ventilation of the intermediate and deep oceans in high latitudes by incorporating an outcrop connecting all sublayers to the atmosphere.

[p] These ranges represent the impact of alternative assumptions about the "unknown carbon sink" that absorbs the unaccounted-for carbon in the carbon cycle. Two sensitivities were analyzed: 1) a high case, where the size of the unknown sink increases at the same rate as atmospheric CO_2 levels compared with preindustrial levels; and 2) a low case, where the size decreases to zero exponentially at 2% per year.

[q] Heat diffusion in the oceans is modeled as a purely diffusive process. To capture some of the uncertainty regarding actual heat uptake, the base case eddy-diffusion coefficient of 0.55×10^{-4} m^2/sec was increased to 2×10^{-4} and decreased to 2×10^{-5} m^2/sec. Climate sensitivity had a measurable effect on these results, so this impact is illustrated as well.

[r] The atmospheric lifetime of CFC-11, 65 years in the RCW case, was varied from 55 to 75 years. Increases or decreases in the atmospheric concentration of CFC-11, however, tend to be offset by corresponding decreases or increases in atmospheric concentrations of other trace gases, such as other CFCs and CH_4.

[s] The amount of stratospheric ozone depletion due to the chlorine contained in CFCs was increased from 0.03% to 0.20% decline in total column ozone/$(ppb)^2$ of stratospheric chlorine.

[t] The rate at which tropospheric ozone forms as a result of CH_4 abundance is estimated with a parameter in the atmospheric composition model. In the RCW case, this variable for the Northern Hemisphere is a 2% change in tropospheric ozone for each percentage change in CH_4 concentration; it was changed to 0.4% in the sensitivity analysis.

[u] Tropospheric OH formation is affected by the level of NO_x emissions. A 0.1% OH change for every 1% change in NO_x emissions for the Northern Hemisphere was assumed in the RCW case; in the sensitivity analysis, a range of 0.05% to 0.2% was evaluated.

[v] For this analysis we assumed that a 2°C increase in realized warming would alter ocean circulation patterns sufficiently to shut off net uptake of CO_2 and heat by the oceans.

[w] We assumed that with each 1°C increase in temperature, an additional 110 Tg CH_4 from methane hydrates, 12 Tg CH_4 from bogs, and 7 Tg CH_4 from rice cultivation would be released annually.

[x] This case illustrates the combined impact of several types of biogeochemical feedbacks: 1) methane emissions from hydrates, bogs, and rice cultivation (see footnote above); 2) increased stability of the thermocline, thereby slowing the rate of heat and CO_2 uptake of the deep ocean by 30% due to less mixing; 3) vegetation albedo, which is a decrease in global albedo as a result of changes in the distribution of terrestrial ecosystems by 0.06% per 1°C warming; 4) disruption of existing ecosystems, resulting in transient reductions in biomass and soil carbon at the rate of 0.5 Pg C per year per 1°C warming; and 5) CO_2 fertilization, which is an increase in the amount of carbon stored in the biosphere in response to higher CO_2 concentrations by 0.3 Pg C per ppm.

would be 12% lower than the estimate for the RCW scenario. If higher CO_2 concentrations greatly fertilize the biosphere (removing some CO_2 from the atmosphere), the equilibrium warming commitment in 2100 could be reduced by as much as 14%. In our highly simplified model of the ocean, heat uptake is controlled by a single diffusion parameter. Adjusting this parameter over a wide but plausible range of values has a large impact on the rate of warming, decreasing the warming realized in 2100 in the RCW scenario by 14-21% or increasing it by 9-16% (for a climate sensitivity to doubled CO_2 of 2-4°C).

A speculative, but potentially important suggestion, is that the role of the oceans could change suddenly as one consequence of climatic change. To provide a preliminary indication of the importance of this potential feedback process we have examined a hypothetical case in which warming by 2°C triggers a change in ocean circulation that prevents the ocean from absorbing any additional CO_2 or heat. The result is a dramatic increase in realized warming by 40 to 60% in 2100. Also quite uncertain, but potentially important, are a number of other biogeochemical feedback processes, such as release of methane contained in near-shore ocean sediments, changes in surface reflectivity due to shifts in vegetation zones, and changes in biospheric carbon storage. Taken together, these feedback processes could strongly amplify climatic change, increasing realized warming in 2100 by 20-40% (assuming the climate sensitivity to doubled CO_2 is 2-4°C) (Table 5).

EMISSIONS REDUCTION STRATEGIES BY ACTIVITY

Many individually modest sources are in combination responsible for the greenhouse gas buildup. Anthropogenic emissions of greenhouse gases can be categorized as arising from energy production and use, industrial activity (including the use of CFCs), agricultural practices, and changes in land-use patterns (including deforestation) (Figure 15). It is useful to

FIGURE 15

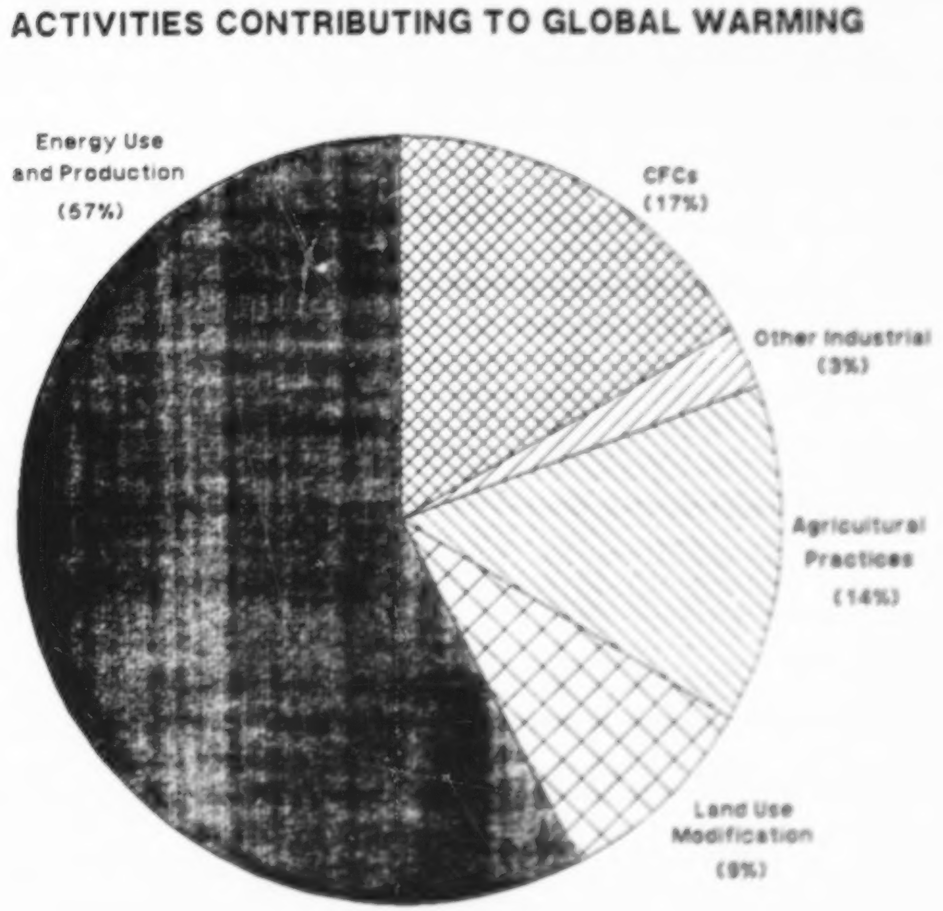


Figure 15. Estimated contribution to greenhouse warming for the 1980s, based upon each activity's share of greenhouse gas emissions, weighted by the greenhouse gas contributions to global warming shown in Figure 3.

examine current and potential future emissions and technical and policy options available for reducing emissions in each of these sectors individually.

Energy Production and Use

Past, Present, and Future Emissions

The largest single factor affecting greenhouse gas emissions is the consumption of energy from carbon-based fossil fuels. Between 1950 and 1985 annual global primary energy consumption grew from 80 to 290 exajoules (EJ),[2] and annual CO_2 emissions grew from 1.6 to 5.2 petagrams of carbon (Pg C).[3] These CO_2 emissions are the dominant reason for the increasing atmospheric concentrations shown in Figure 1. Even though emissions have been relatively stable during the last decade, atmospheric concentrations have continued their steady rise because CO_2 emissions remain substantially greater than uptake by the oceans and any other sinks.

The almost four-fold increase in energy consumption during the last 35 years was accompanied by a significant shift in its global distribution. In 1950 countries belonging to the Organization for Economic Cooperation and Development (OECD) consumed about three-fourths of all commercial energy supplies, the centrally-planned economies of Europe and Asia, 19 percent, and developing countries, 6 percent. By 1985 OECD countries consumed just over one-half of all commercial energy globally, while the European and Asian centrally-planned economies and the developing countries had increased their relative share to 32 percent and 15 percent, respectively.

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[2] One exajoule = 10^{18} joules = 0.95 quadrillion British Thermal Units = 0.95 Quad.

[3] One petagram = 10^{15} grams.

Developing and Eastern Bloc Countries are potentially large sources of future emissions. Growth in energy use is driven almost entirely by countries outside the OECD in all of the scenarios developed for this study. The OECD share of primary energy consumption falls to 25% by 2100 in the SCW and to as little as 17% in the RCW.[4] Growth in demand outside the OECD nonetheless drives up global energy demand significantly in these scenarios. Total end-use energy demand increases from 220 EJ in 1985 to 320 EJ in 2025 in the SCW versus 420 EJ in the RCW.[5]

Greater improvements in energy efficiency in the SCWP and RCWP cases reduce end-use demand in 2025 by 13% and 15%, respectively, relative to the No Response scenarios. End-use demand in the Rapid Reduction scenario is 20% lower than in the RCW by 2025. Increases in energy efficiency account for about one-fourth of the warming reduction in the RCWP versus the RCW case in 2050.

While policies affecting demand will have the largest impact on near-term greenhouse gas emissions, changes in the supply mix are also critical in influencing emissions over the long term. Global primary energy supply is shown by source for the four scenarios in Figure 16. Growth in primary energy consumption is substantially higher than growth in end-use energy demand because of increased requirements for electricity and synthetic fuel production, which involve substantial conversion losses. This is most dramatic in the RCW, where

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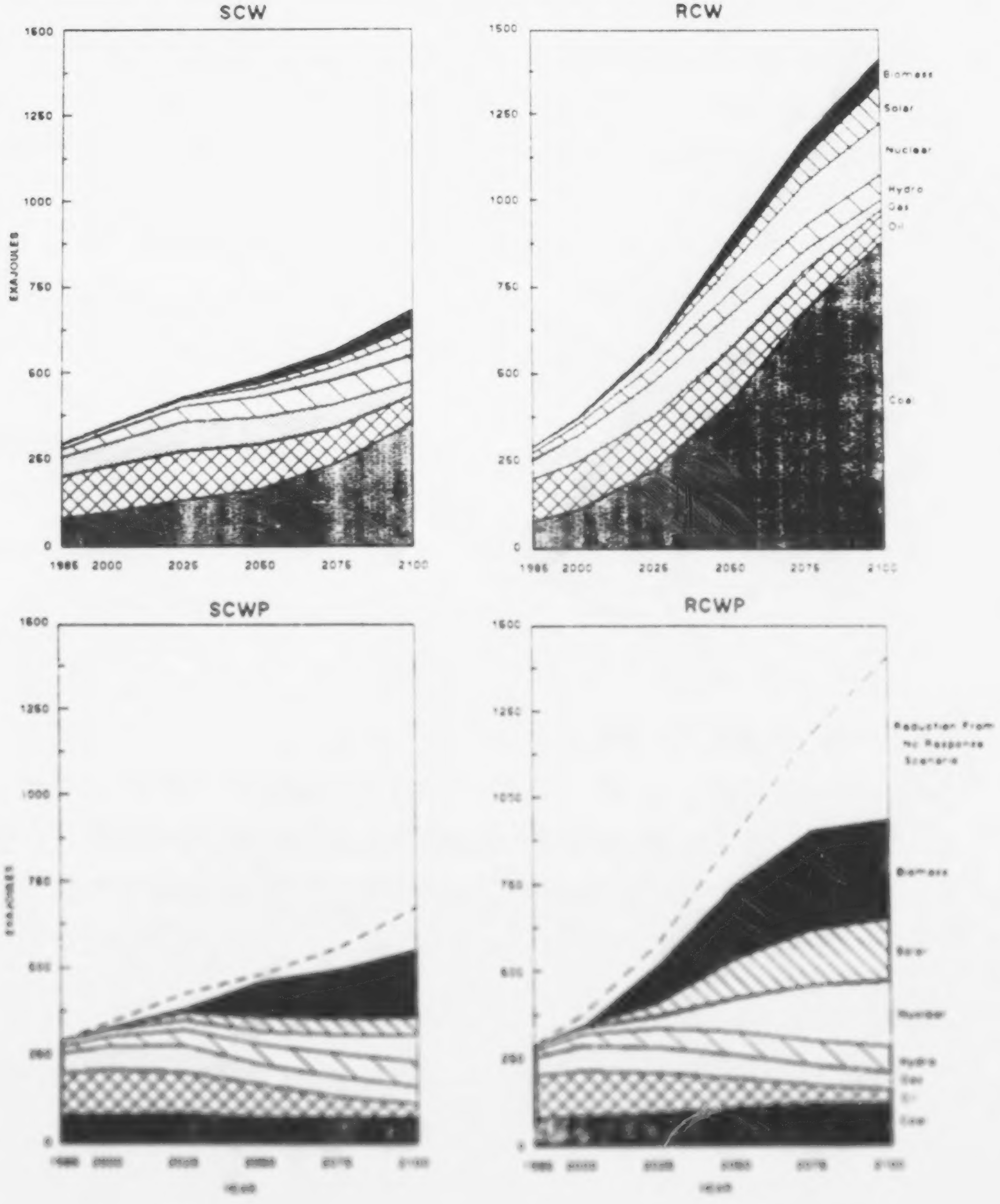
[4] Primary energy includes conversion losses, such as in electricity and synfuels production. The primary energy equivalent of nuclear, hydro, and solar electricity is calculated on the basis of the average efficiency of fossil-fuel-fired power plants.

[5] End-use energy is based on final consumption, with electricity valued at 3.6 megajoules per kilowatt-hour.

FIGURE 16

PRIMARY ENERGY SUPPLY BY TYPE

(Exajoules)



primary energy consumption increases from 290 EJ in 1985 to 580 EJ in 2025 and 1410 EJ in 2100; a 100% and 380% increase, respectively, compared with 90% and 260% increases in end-use demand.

Carbon dioxide emissions could grow by a factor of 2 to 5 during the next century if stabilizing policies are not adopted. Heavy reliance on coal in both the SCW and RCW scenarios leads to large increases in both CO_2 and CH_4 emissions. In the SCW, energy-related emissions of CO_2 increase from 5.1 petagrams of carbon (Pg C) in 1985 to 7.2 Pg C in 2025 and 10.8 Pg C in 2100. Emissions reach more than twice this level in the RCW scenario: 10.1 and 24 Pg C in 2025 and 2100, respectively. Emissions of CH_4 from fuel production, predominantly coal mining, grow even more dramatically. The estimated emissions from fuel production in 1985 are 60 teragrams of CH_4 (Tg CH_4) or just over 10% of the total.[6] In the SCW this source increases to 86 Tg CH_4 in 2025 and 160 Tg CH_4 in 2100. The corresponding values for the RCW are 130 Tg CH_4 in 2025 and 360 Tg CH_4 in 2100, about 20 and 30% of the total, respectively.

Technical options are available that, if adopted, could stabilize carbon dioxide emissions. The combination of higher efficiency and greater reliance on non-fossil fuels assumed in the Stabilizing Policy scenarios substantialy curtails CO_2 and CH_4 emissions. In both the SCWP and RCWP cases, CO_2 emissions from energ use reach only 5.5 Pg C in 2025, after which time they decrease, reaching 3.2 and 4.3 Pg C by 2100in the two cases, respectively. Similarly, CH_4 emissions from fuel production remain relatively constat in both of these scenarios. Increased reliance on non-fossil fuels in the RCWP is responsible forabout one-fourth of the reduction in warming in this scenario relative to the RCW in 2050.

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[6] 1 teragram = 10^{12} grams.

Despite the large range of outcomes illustrated by the four scenarios discussed here, none of the global rates of change are unprecedented (Table 7). Global reductions in aggregate energy intensity generally fall within the range of 1-2% per year; the lower value is consistent with long-term trends and the higher value is consistent with recent experience. Reductions in the amount of carbon emitted per unit of energy consumed (carbon intensity) varies from 0.0 to 1.3% per year with significant declines only apparent in the Stabilizing Policy cases. These values are not unprecedented, as carbon intensity declined by an average of 1.5% per year between 1925 and 1985 due to increased reliance on oil and gas in preference to coal (but coal is expected to regain market share in the future in the absence of policy changes).

Energy-related emissions, other than of CO_2 and CH_4, are strongly affected by the type of control technology employed in addition to the total amount and type of energy used. Emissions of CO and NO_x associated with energy use can be expected to increase almost as rapidly as primary energy consumption in the absence of new policies. On the other hand, in the Stabilizing Policy scenarios, NO_x emissions are roughly constant and CO emissions are cut by more than half. This assumes that the rest of the world gradually adopts control technology similar to that required of new mobile and stationary sources in the United States today and that industrialized countries adopt standards consistent with the use of Selective Catalytic Reduction or Inter-cooled Steam-Injected Gas Turbine technology in utility and industrial applications after 2000, with developing countries following after 2025. Emission controls account for about 4% of the 2050 warming reduction in the RCWP relative to the RCW.

Energy Technologies to Reduce Greenhouse Gas Emissions

The introduction of technologies and practices that use less energy to accomplish a given task will have the largest impact on global warming in the near term. We

TABLE 7

Key Global Indicators for Energy and CO_2

Parameter	Scenario	1985	2025	2100
GNP/capita (1000 1988$)	SCW, SCWP	3.0	3.7	7.1
	RCW, RCWP		6.7	35.6
Primary Energy (EJ)	SCW	290	430	680
	RCW		580	1410
	SCWP		380	550
	RCWP		520	940
Fossil Fuel CO_2 (Pg C)	SCW	5.1	7.2	11.1
	RCW		10.3	24.4
	SCWP		5.5	3.2
	RCWP		5.5	4.3

		1985-2025	2025-2100
GNP/capita (%/yr)	SCW, SCWP	0.5	0.9
	RCW, RCWP	2.0	2.3
Energy/GNP (%/yr)	SCW	-1.1	-0.8
	RCW	-1.6	-1.4
	SCWP	-1.3	-1.0
	RCWP	-1.9	-1.8
Fossil Fuel CO_2/Energy (%/yr)	SCW	-0.1	-0.0
	RCW	0.0	-0.0
	SCWP	-0.5	-1.2
	RCWP	-1.3	-1.1

estimate that accelerated improvements in energy efficiency account for about 25% of the difference between the RCWP and the RCW cases in 2050 (we note that this occurs even though fairly rapid improvements are already assumed in the RCW case). We list below examples of potential efficiency improvements that can be made in the various sectors of the economy.

Transportation - A number of technologies have already been demonstrated that could increase automobile fuel efficiency from current levels for new cars (25-33 mpg or 9.4-7.1 liters/100 km) to better than 50 mpg (4.7 liters/100 km); these technologies may pay for themselves in fuel savings over the lifetime of the vehicle. Further improvements can increase fuel efficiency to more than 80 mpg (less than 3 liters/100 km), although they do not appear to be cost effective at current U.S. gasoline prices. The RCWP scenario assumes that new cars in the industrialized countries achieve an average of 40 mpg (5.9 liters/100 km) by 2000. Global fleet average fuel efficiency reaches 50 mpg (4.7 liters/100 km) in 2025 and 75 mpg (3.1 liters/100 km) in 2050 (somewhat lower rates of efficiency improvement are assumed in the SCWP scenario). In addition, major fuel efficiency improvements in diesel trucks and aircraft are possible. The Rapid Reduction case assumes more aggressive measures to improve efficiency: new vehicles achieve an average of 50 mpg (4.7 liters/100 km) by 2000.

Residential and Commercial - Improved building shells, lighting, heating and cooling equipment, and appliances are currently commercially available. The most efficient new homes currently being built use only 30% as much heating energy per unit of floor area as the average existing house in the United States. Advanced prototypes and design calculations indicate that new homes could technically be built that use only 10% of current average energy requirements. About 20% of U.S. electricity is consumed for lighting, mainly in residential and commercial buildings. A combination of currently available advanced technology and careful design has been shown to cost-effectively reduce energy requirements for lighting by more than 75%. The RCWP scenario assumes that the average reduction in energy use per unit of residential and commercial floor space by 2025 is as much as 75% for fuel and 50% for electricity in the U.S. Smaller improvements are assumed in other regions and in the SCWP scenario.

Industrial Energy - Advanced industrial processes are available that can significantly reduce the energy required to produce basic materials. This is especially true when combined with recycling. For example, new technology developed in Sweden uses about half as much energy per unit of steel production as the current U.S. average. Electric motors are estimated to account for about 70% of U.S. industrial electricity use. Several case studies show that improved motors and motor controls are commercially available, which could reduce energy consumption by electric motors by at least 15% relative to current averages.

Developing countries can also significantly improve energy efficiency. Per capita energy consumption is very low in developing countries, but there is a large potential to increase efficiency because energy use per unit of GNP is often extremely high. Indeed, the imperative for energy efficiency may be even stronger in developing countries to the extent that expending scarce capital on expanding energy supply systems can be avoided. Some of the technical options described above may be directly applicable in developing as well as industrialized countries, while alternative approaches suited to available resources will often be needed. In many cases improved management of existing facilities could have large payoffs.

Research on non-fossil energy technologies is a critical need. The development of attractive non-fossil energy sources is critical to the success of any climate stabilization strategy over the long term. Increased penetration of solar and advanced biomass technologies contribute little to reduced warming in 2025, but they are responsible for 24% of the difference between the RCWP and the RCW case in 2050, and over 30% of this difference in 2100. The exact mix of non-fossil technologies assumed in the policy scenarios is rather arbitrary, but makes little difference to greenhouse gas emissions. Some particularly promising non-fossil technologies are described below.

Hydro and Geothermal Power - Hydroelectric power is already contributing the equivalent of about 7% of global primary energy production and geothermal power is making a small (less than 1%) but important contribution. There is potential to expand the contribution of these sources, although good sites are limited and environmental and social impacts of large-scale projects must be considered carefully. Hydroelectric and geothermal power expands to 12% of global primary energy production in the SCWP scenario, but only maintains a roughly constant share of the higher level of production in the RCWP case.

Biomass Energy - Biomass is currently being extensively utilized, accounting for roughly 10% of global energy consumption, primarily in traditional applications (e.g., cooking), which are not included in most accounts of commercial energy use. Current and emerging technologies could vastly improve the efficiency of biomass use. In the near term there is a substantial potential to obtain more useful energy from municipal and agricultural wastes. More advanced technologies for producing, collecting, and converting biomass to gaseous and liquid fuels and electricity could become economically competitive within a decade. The prospects for integrating biomass gasification with advanced combustion turbines is particularly promising. Environmental and societal impacts related to large-scale biomass use, which would have to be addressed, include competition with food production, ecological impacts, and emissions of volatile organic compounds. In the SCWP scenario biomass energy supplies 21% of primary energy needs in 2050 and 35% in 2100. Biomass supplies about 30% of primary energy by 2050 in the RCWP scenario.

Solar Energy - There is a large range of solar options. Direct use of solar thermal energy, either passively or in active systems, is already commercial for many water and space heating applications. Wind energy systems are also currently commercial for some applications in some locations. In recent years engineering advances have resulted in significant cost reductions and performance improvements. Solar photovoltaic (PV) cells are currently competitive for many remote power generation needs, especially in developing countries. Dramatic progress has been made recently in reducing the costs of producing PV systems, particularly with thin-film amorphous silicon technology. If current research and manufacturing development efforts reach their objectives, PV could play a major role in meeting energy needs in the next century. In the SCWP scenario solar sources of electricity are equivalent to 9% of primary energy supply from 2050 onward. A larger contribution is envisioned in the RCWP scenario: 15% in 2050, increasing to almost 20% in 2100.

Nuclear Power - Nuclear fission produces about 5% of global primary energy supplies and its share is currently growing due to the completion of powerplants ordered during the 1970s. High cost and concerns about safety, nuclear proliferation, and radioactive waste disposal, however, have brought new orders to a halt in many countries. Advanced designs, in particular the Modular High Temperature Gas-cooled Reactor, have recently been proposed in an attempt to overcome some of these problems. The role of nuclear power could be significantly expanded in the future if these efforts are successful in restoring public confidence in this energy source. Nuclear power's contribution to primary energy supply increases to 8% in 2050 and 14% in 2100 in the SCWP case and 13% in 2050 and 20% in 2100 in the RCWP case.

Energy Policy Options

No single policy approach by itself is likely to be both effective and acceptable as a means of achieving substantial reductions in greenhouse gas emissions from energy production and use. Strategies appropriate for developing countries, for example, may be quite different from those that are appropriate for the United Staes. However, many complementary policy options are available that offer differing relative advantages for reducing emissions.

Proper pricing of energy services may be most important. It is critical to encourage both increases in end-use efficiency andthe development of energy sources that emit no CO_2. Current market prices of fossil fuels do notreflect the risk of climatic change and provide no assurance that limiting greenhouse gas emissions will be a consideration in purchase and investment decisions. A direct means of providing incenties to reduce emissions is to impose a fee on fossil fuels in proportion to their relative contribution to global warming. Regulatory programs may be an important complement when pricing strategies are not effective, either because of market failures or because of inequitable impacts o some regions or income groups. Directing research and development priorities toward enery sources that emit no CO_2 is essential to assure the availability of attractive options over the longe term. Other important policy options include the selective use of government procurement to stimiate markets and promote technological alternatives, and technical assistance and information program.

Industrial Activity

Three significant non-energy sorces of greenhouse gases are associated with industrial activity: the release of halocarbons during tir production and use; methane emissions from waste disposal in landfills; and carbon dioxide emsions from cement manufacture.

Production and Use of Halocarbons

Chlorofluorocarbons, halons, and chlorocarbons (collectively, halocarbons) are man-made chemicals containing carbon, chlorine, fluorine, and bromine (HCFCs contain hydrogen as well). Table 8 lists the major halocarbons with their chemical formulae and major uses. CFCs were originally commercialized in the 1930s as non-toxic, non-flammable, and highly stable coolants for refrigerators. They were first used as propellants during World War II, and as blowing agents for foam products during the 1950s. CFCs are also used in gas sterilization of medical equipment and instruments, solvent cleaning of manufactured parts, and miscellaneous other processes and products such as liquid food freezing. Halons were developed in the 1970s and are used primarily as fire extinguishants. Chlorocarbons are used primarily as solvents and chemical intermediates. The primary chlorocarbons are carbon tetrachloride and methyl chloroform. Production of halocarbons has grown rapidly as new uses have developed.

Halocarbons have been identified as a serious threat to the stratospheric ozone layer. International negotiations to protect the stratosphere began in 1981 under the auspices of the United Nations Environment Programme (UNEP). These negotiations culminated in September 1987 when "The Montreal Protocol on Substances That Deplete the Ozone Layer" (or the Montreal Protocol) to reduce the use of CFCs and halons was initialed. The Montreal Protocol came into force on January 1, 1989, and has been ratified by 31 countries, representing over 90% of current world consumption of these chemicals (as of January 11, 1989).

Further reductions in CFCs would be needed to stabilize concentrations. The major provisions of the Montreal Protocol include a 50% reduction from 1986 levels in the use of CFC-11, -12, -113, -114, and -115 by 1998; a freeze on the use of Halon-1211, -1301, and -2402 at 1986

TABLE 8

Major Chlorofluorocarbons, Halons, And Chlorocarbons: Statistics And Uses

Chemical	1986 Atmospheric Concentration (pptv)	Atmospheric Lifetime (Years)	Current Annual Atmospheric Concentration Growth Rates (%/yr)	Major Uses
Chlorofluorocarbons				
CFC-11 ($CFCl_3$)	226	75^{+32}_{-17}	4	Aerosols, Foams
CFC-12 (CF_2Cl_2)	392	111^{+289}_{-46}	4	Aerosols, Refrigeration
HCFC-22 ($CHClF_2$)	~100	20	7	Refrigeration
CFC-113 ($C_2Cl_3F_3$)	30-70	90	11	Solvents
Halons (Bromofluorocarbons)				
Halon-1211 ($CBrClF_2$)	~2	25	>10	Fire extinguisher
Halon-1301 ($CBrF_3$)	~2	110	>10	Fire extinguisher
Chlorocarbons				
Carbon tetrachloride (CCl_4)	75-100	~50	1	Production of CFC-11 and CFC-12
Methyl chloroform (CH_3CCl_3)	125	5.5-10	7	Solvents

levels starting in approximately 1992; and a delay of up to 10 years in compliance with the protocol for developing countries with low levels of use per capita. As a result of this historic agreement, the very high growth rates in CFC concentrations assumed in some previous studies are unlikely to occur. However, because of the long atmospheric lifetimes of CFCs, the probability that not all countries will participate in the agreement, and the provision for increased use in developing countries, CFC concentrations will still rise significantly in the future unless the protocol is strengthened (see Figure 5). Despite assuming that at least 65% of developing countries and 95% of industrialized countries participate in the agreement, the total contribution of halocarbons to the greenhouse effect increases by more than a factor of 4 in the SCW and by a factor of 6.5 in the RCW scenario by 2100.

Promising chemical substitutes, engineering controls, and process modifications have now been identified that could eliminate most uses of CFCs. In the policy scenarios we assume that the use of CFCs and Halons is phased out and that emissions of methyl chloroform are frozen (no additional growth in CFC substitutes is assumed as a result of the phaseout). Even under these assumptions total weighted halocarbon concentrations increase significantly from 1985 levels in part because the chemical substitutes contribute significantly to greenhouse forcing, but the final concentrations are about one-third of the level in the corresponding No Response scenarios. The greenhouse forcing potential of CFC substitutes will have to be carefully evaluated to improve estimates of their potential role in climate change. In our analysis, phasing out CFCs was responsible for 6% of the decrease in warming in the RCWP compared with the RCW in 2050.

Waste Disposal

Landfills are a small but potentially controllable source of methane. Waste disposal in landfills and open dumps generates methane when decomposition of the organic material becomes anaerobic; approximately 80 percent of urban solid wastes is currently disposed of in one of these ways.

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Landfilling (compaction of wastes, followed by daily capping with a layer of clean earth) is most common in industrialized countries, while open pit dumping is the most common "managed" disposal method in developing countries (30-50% of solid wastes generated in cities in developing countries is currently uncollected). Most of the decomposition in landfills and some of the decomposition in open pits is anaerobic, resulting in annual methane emissions of 30-70 Tg CH_4, about 10% of the total source.

Disposal of municipal solid waste in industrialized nations increased by 5% per year during the 1960s, and by 2% per year in the 1970s. Landfilling is not expected to increase very much in industrialized countries in the future, but it can be expected to increase dramatically in developing countries as population growth, urbanization, and economic growth all imply increased disposal of municipal solid waste. The growth of landfill methane emissions in developing countries is assumed to be related to per capita income in a simple fashion, although growth is curtailed as current per capita levels in industrialized countries are approached. The result is a three- and five-fold increase in methane emissions in the SCW and RCW scenarios, respectively, reaching 13-15% of the total methane budget by 2100. The Stabilizing Policy scenarios assume that gas recovery systems and waste reduction policies will be adopted, resulting in roughly constant global emissions from landfills.

Cement Making

Carbon dioxide is emitted in the calcining phase of the cement-making process when calcium carbonate ($CaCO_3$) is converted to lime (CaO). For every ton of cement produced 0.14 tons of carbon are emitted as CO_2 from this reaction. Generally, even more CO_2 is emitted from the fuel used to drive the process (these combustion emissions are accounted for as part of industrial energy-use emissions). World cement production has increased at an average annual rate of approximately 6% since the 1950s, from 130 million tons in 1950 to about one billion tons currently. Thus, current

CO_2 emissions from calcining are 0.14 billion tons of carbon (0.14 Pg C). The share of global production in industrialized countries has declined during this period, and this trend is expected to continue because demand in these countries is saturating. Emissions of CO_2 from cement making, projected using the per capita income approach described in the **Waste Disposal** section, increase by two- to three-fold in the SCW and RCW scenarios by the year 2100. (Emissions remain less than 0.5 Pg C/yr in all cases.) In the Stabilizing Policy scenarios, advanced materials are assumed to reduce the demand for cement (relative to the No Response scenarios), but emissions still grow by about a factor of 2.

Changes in Land Use

Deforestation and biomass burning are significant sources of CO_2, CO, CH_4, NO_x, and N_2O. Globally, the world's forest and woodland areas have been reduced by about 15% since 1850, primarily to accommodate the expansion of cultivated lands. The largest decreases in forest area during this period have occurred in Africa, Asia, and Latin America; Europe is the only region that has experienced a net increase. It is generally estimated that approximately 11 million hectares (Mha) of tropical forests are currently lost each year, while only 1.1 Mha are reforested per year. Recent analysis of remote sensing data from Brazil, however, suggest that in 1987, 8 Mha were cleared in the Brazilian Amazon alone. Estimates of net emissions of CO_2 to the atmosphere due to changes in land use (deforestation, reforestation, logging, and changes in agricultural area) in 1980 range from 0.4-2.6 Pg C, almost entirely from tropical countries. This accounts for approximately 10-30% of annual anthropogenic CO_2 emissions to the atmosphere. Of the estimated net release of carbon from tropical deforestation in 1980 about half was from Brazil, Indonesia, Colombia, the Ivory Coast, Thailand, and Laos.

Biomass burning, related to deforestation, shifting cultivation, burning agricultural waste, and fuelwood use, contributes roughly 10-25% of total annual CH_4 emissions, 5-15% of N_2O emissions, 15-30% of NO_x emissions, and 20-35% of the CO emissions. In addition, biomass burning and land clearing results in elevated biogenic emissions of NO_x and N_2O from the soil for an extended period after the burn.

Most tropical forests could be lost during the next century. The causes of deforestation are complex and vary from country to country, making it difficult to directly tie assumptions about deforestation rates to the economic and demographic assumptions of the general scenarios. Qualitatively, we assume that in a Slowly Changing World continued poverty, unsustainable agricultural practices, and rapid population growth lead to continuously increasing pressure on remaining forests. The rate of deforestation is assumed to increase from current levels at the rate of population growth for this scenario. Under this assumption the rate of tropical deforestation increases from 11 million hectares per year (Mha/yr) in 1980 to 34 Mha/yr in 2047, when the available area of forests in Asia is exhausted. As a result, CO_2 emissions from deforestation increase rapidly from 0.7 Pg C/yr to more than 2 Pg C/yr in 2047 before the Asian forests are exhausted. Latin American and African forests are exhausted by 2075, reducing emissions drastically (Figure 17).

In a Rapidly Changing World improved agricultural practices and the substitution of modern fuels for traditional uses of wood could ease the pressure on forests. Nonetheless, clearing of forest lands for agriculture, pasture, logging, and speculation could continue apace, even if small areas are set aside as biological preserves. In this scenario tropical deforestation is assumed to increase very gradually, reaching 15 Mha/yr in 2097, before the unprotected forest areas of Latin America are exhausted. Total emissions are almost the same as in the SCW, but they are spread out over a longer period. Emissions are close to 1 Pg C/yr from 2000 to 2100.

CO2 EMISSIONS FROM DEFORESTATION

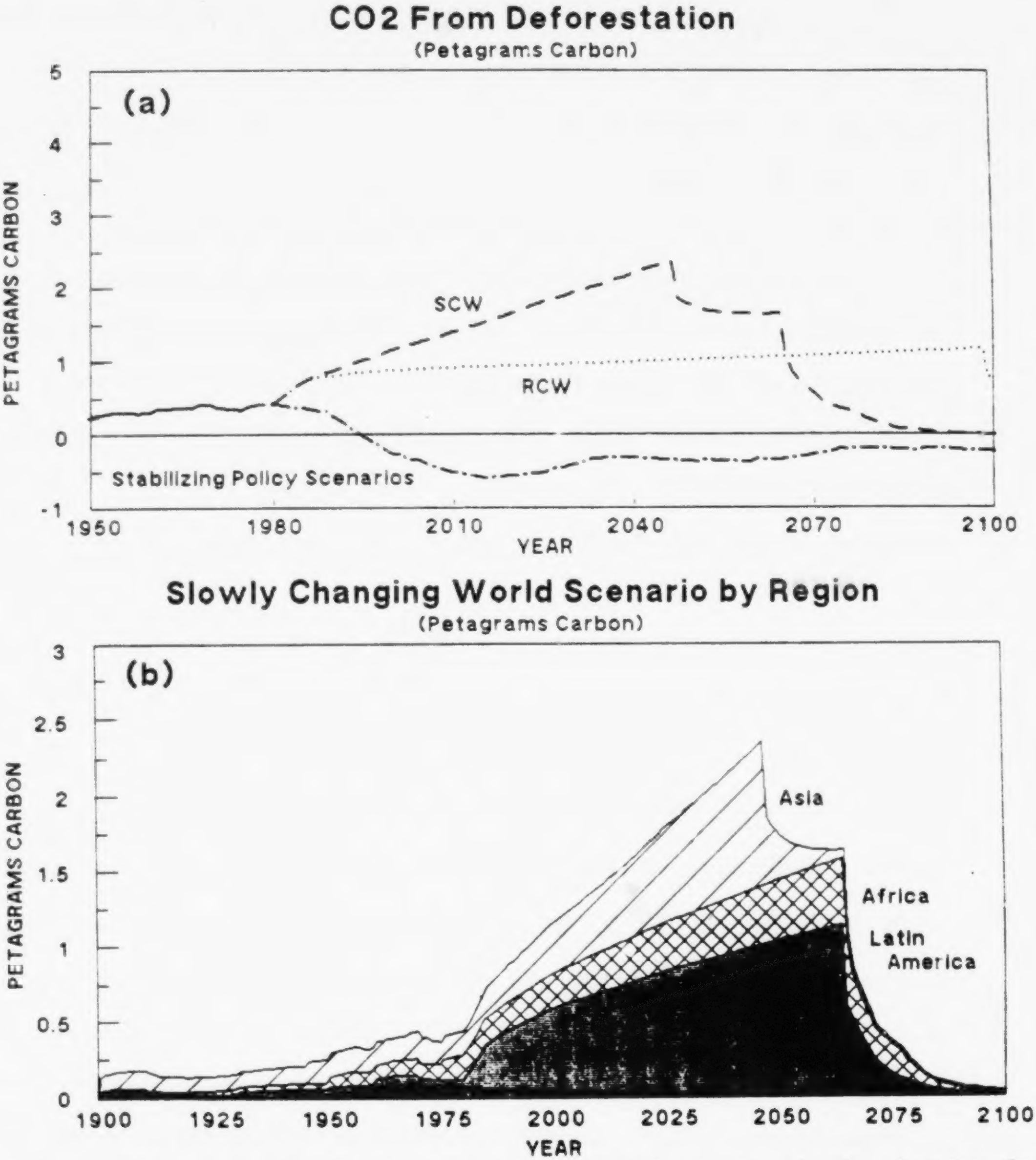

Figure 17. (a) Annual emissions of CO_2 from deforestation in units of carbon, based on the low estimate of initial biomass. The lowest curve (the dashed and dotted line) is assumed in both the SCWP and RCWP scenarios and indicates net uptake of CO_2 due to reforestation after 2000.

(b) Regional detail for the SCW scenario. Sharp declines in emissions follow the exhaustion of forests in Asia, Africa, and Latin America.

Reforestation is a potentially cost-effective means of reducing net carbon dioxide emissions. In the Stabilizing Policy scenarios it is assumed that the biosphere is transformed from a source to a sink for carbon by 2000. A combination of policies succeed in stopping deforestation by 2025 while up to 1000 Mha is reforested by 2100. Forests reach their peak absorption of 0.7 Pg C/yr before 2025. (The land area required depends on the productivity of the reforested land. We have used a conservative estimate; if the productivity were higher, then less than 1000 Mha would be required or the maximum sink would be more than 0.7 Pg C/y.) The size of this sink declines gradually after 2025 as forests reach their maximum size and extent. Only land that once supported forests and is not intensively cultivated is assumed to be available for reforestation. These lands include 85% of the area currently involved in shifting cultivation (370 Mha) under the assumption that this practice is replaced by sustainable low input agriculture. In addition, some fraction of the fallow agricultural land in the temperate zone (250 Mha), planted pasture in Latin America (100 Mha), and degraded land in Africa and Asia (400 Mha) is assumed to be reforested. Of the reforested land, about 380 Mha is assumed to be in plantations, which is sufficient to produce the biomass energy requirements of the RCWP case with the productivity goals established by the Department of Energy.

Reversing deforestation could be a very cost-effective policy response to potential climatic change. Although a vast area of land would have to be involved to make a significant contribution to reducing net CO_2 emissions, preliminary estimates suggest that the cost of absorbed or conserved carbon could be extremely low in comparison to other options. Furthermore, a reforestation strategy could offer a stream of valuable ecological and economic benefits in addition to reducing CO_2 concentrations, such as forest products, maintenance of biodiversity, watershed protection, nonpoint pollution reduction, and recreation. Devising successful forestry programs presents unique challenges to scientists and policy makers because of the vast and heterogeneous landscape, uncertain ownership, lack of data, and the need for more research and field trials. Investments that would be small by the standards of the energy industry, however, could make an enormous impact on forestry. Reforestation accounts for almost one-fifth of the decrease in warming by 2050 in the RCWP versus the RCW scenarios.

Agricultural Practices

Three agricultural activities contribute to atmospheric concentrations of greenhouse gases in addition to those that have been discussed regarding changes in land use: enteric fermentation in domestic animals; rice cultivation; and nitrogenous fertilizer use.

Methane emissions from animals may increase significantly over the next century. Methane is produced as a by-product of enteric fermentation in herbivores, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream. The highest CH_4 losses are reported for ruminants (e.g., cattle, dairy cows, sheep, buffalo, and goats) in which 4-9% of total energy intake is released as methane. Of the annual global source of 400 to 600 Tg CH_4, domestic animals contribute approximately 65-85 Tg. Of these emissions approximately 57% comes from cattle and 19% from dairy cows. The domestic animal population has increased considerably during the last century. Between the early 1940s and 1960s, increases in global cattle populations averaged 2% per year. Since the 1960s, the rate of increase has slowed somewhat, to 1.2%. By comparison, the average annual increase in global human population since the 1960s has been about 1.8%. Future demand for agricultural products will depend more on population than on income levels. Based on a global agriculture model, methane emissions from enteric fermentation are estimated to increase by about 125% from 1985 to 2100 in both the SCW and the RCW scenarios as the much higher incomes in the RCW largely offset the somewhat higher populations in the SCW.

Methane emissions from rice cultivation are likely to increase more slowly. Methane produced by anaerobic decomposition in flooded rice fields escapes to the atmosphere by bubbling up through the water column, diffusing across the water/air interface, and transport through the rice plants. The amount of CH_4 released to the atmosphere is a complex function of rice species, number and duration of harvests, temperature, irrigation practices, and fertilizer use. Rice fields are estimated to contribute 60-170 Tg CH_4 per year to the atmosphere, or approximately 10-30% of the global flux. This large range reflects a paucity of data, particularly from Asia, where 90% of rice cultivation occurs. From 1950 to 1984, harvested rice paddy area increased approximately 40%, from 103 to 148 Mha, and average global yields doubled, from 1.6 to 3.2 tons per hectare. Methane emissions are probably primarily a function of area under cultivation rather than yield, although yield could influence emissions, particularly if more organic matter is incorporated into the paddy soil. The land area used for rice production, and thus the CH_4 emissions from this source increases by only about 50% by 2100 in both the SCW and RCW scenarios (production per hectare increases by 80-100%).

Nitrous oxide is released through microbial processes in soils, both through denitrification and nitrification. The use of nitrogenous fertilizer enhances N_2O fluxes since some of the applied N is converted to N_2O and released to the atmosphere. The amount of N_2O released varies greatly and depends on rainfall, temperature, the type of fertilizer applied, mode of application, and soil conditions. Approximately 70 million tons (70 Tg) of nitrogen were applied in the form of nitrogenous fertilizers worldwide in 1984-85. A preliminary estimate suggests that this produced N_2O emissions of 0.14-2.4 Tg N out of the global source of 11-17 Tg N per year. Satisfying the demands of increasing populations with a finite amount of land requires more intensive cultivation resulting in a 160% increase in fertilizer use between 1985 and 2100 in both the SCW and RCW scenarios.

Future research and technological changes could reduce agricultural emissions. In the policy scenarios we do not assume changes in the demand for agricultural commodities, but rather changes in production systems that could reduce greenhouse gas emissions per unit of product. Although the impact of specific approaches cannot be quantified at present, a number of techniques, such as feed additives for cattle, changes in water management in rice production, and fertilizer coatings, have been identified for reducing methane and nitrous oxide emissions from agricultural sources. The implementation of these options depends on further research and demonstrations. For simplicity we have assumed that methane emissions per unit of rice, meat, and milk production decrease by 0.5% per year (emissions from animals not used in commercial meat or milk production are assumed to be constant). Emissions of nitrous oxide per unit of nitrogen fertilizer applied are also assumed to decrease by 0.5% per year for each fertilizer type. In addition, fertilizer use is assumed to shift away from those types with the highest emissions after 2000. The result of these assumptions is substantially lower agricultural emissions in the policy scenarios relative to the No Response scenarios. Emissions grow by less than a factor of 2 in all cases, and methane emissions from rice remain roughly constant until 2075, after which time they fall by about 20% as the global population stabilizes. Reduced emissions from agriculture, landfills, and cement manufacture accounts for 10% of the reduced warming in the RCWP compared with the RCW scenario in 2050.

THE NEED FOR POLICY RESPONSES

The prospect of global climate change presents policy makers with a unique challenge. The potential scale of the problem is unprecedented. Many choices are available and the consequences of these choices will be profound.

If limiting U.S. and global emissions of greenhouse gases is desired, government action will be necessary. Market prices of energy from fossil fuels, products made with CFCs, forest and agricultural products, and other commodities responsible for greenhouse gas emissions do not reflect the risks of climate change. As a result, increases in population and economic activity will cause emissions to grow in the absence of countervailing government policies.

A Wide Range of Policy Choices

A wide range of policy choices is available for reducing greenhouse gas emissions. There is an important distinction between short-term and long-term policy options. In the short-term, the most effective means of reducing emissions is through strategies that rely on pricing and regulation. In the long-term, policies to increase research and development of new technologies and to enhance markets through information programs, government purchases, and other means could also make a major contribution.

- The most direct means of allowing markets to incorporate the risk of climatic change is to assure that the prices of fossil fuels and other sources of greenhouse gases reflect their full social costs. It may be necessary to impose emission fees on these sources according to their relative contribution to global warming in order to accomplish this goal. This would also raise revenues that could finance other programs. The degree to which such fees are accepted will vary among countries, but acceptability would be enhanced if fees were equitably structured.

- Regulatory programs would be a necessary complement when pricing strategies are not effective or produce undesirable impacts. In the U.S., greenhouse gas emissions are influenced by existing federal regulatory programs to control air pollution, increase energy efficiency, and recycle solid waste. Reducing greenhouse gas emissions could be incorporated into the goals of these programs. New programs could focus directly on reducing greenhouse gas emissions through requirements such as emissions offsets (e.g., tree-planting), performance standards, or marketable permits.

- State and local government policies in such areas as utility regulation, building codes, waste management, transportation planning, and urban forestry could make an important contribution to reducing greenhouse gas emissions.

- Voluntary private efforts to reduce greenhouse gas emissions have already provided significant precedents for wider action and could play a larger role in the future.

- Over the long term, other policies will be needed to reduce emissions and can complement pricing and regulatory strategies. Other policy options include redirecting research and development priorities in favor of technologies that could reduce greenhouse gas emissions, information programs to build understanding of the problems and solutions, and the selective use of government procurement to promote markets for technological alternatives.

The Timing of Policy Responses

The costs and benefits of actions taken to reduce greenhouse gas emissions are difficult to evaluate because of the many uncertainties associated with estimates of the magnitude, timing, and consequences of global climate change, as well as the difficulty of assessing the net social costs of strategies that involve widespread and long-term shifts in technological development. In this situation it may appear to be prudent to delay action to stabilize greenhouse gas concentrations until the magnitude of the problem and the costs of responses are better established. The potential benefits of delay, however, must be balanced against the potential increased risks.

Policy development and implementation can be a lengthy process, particularly at the international level. Any decision to respond to the greenhouse gas buildup cannot be translated immediately into action. Roughly a decade was required for the process that led to international agreement to reduce emissions of CFCs, embodied in the Montreal Protocol, and it will take another decade to implement the agreed-upon reductions. Agreements to reduce other greenhouse gas emissions could take much longer to achieve and implement.

The development of technologies to reduce greenhouse gas emissions will take many years. The majority of emissions are associated with fundamental components of the global economy (transportation, heating and cooling buildings, industrial production, land clearing, etc.), such that reducing emissions by curtailing these activities would be highly disruptive and undesirable. While a large menu of promising technologies have been identified that can meet our needs for goods and services while generating much lower emissions of greenhouse gases, many require additional research and development to become economically competitive. The time required for innovative technologies to be brought to market is unpredictable, but is usually many years. And once a technology is cost-effective, it may take years before it achieves a large market share and decades more for the existing capital stock to be replaced. Depending on the sector, it may take 20-50 years or more to substantially alter the technological base of industrial societies, and the cost of reducing emissions could rise dramatically as the time allowed for achieving these reductions is decreased. While the rate of change can be higher in rapidly developing countries, and may be influenced by government policies, once industrial infrastructure is built, it will be many years before it is replaced.

Industrialized and developing countries could limit the buildup of greenhouse gases in a manner consistent with economic development and other environmental and social goals. The justification for policies that reduce greenhouse gas emissions may be much greater than it would appear from a narrow examination of costs and climatic benefits. Most of the measures proposed to reduce emissions -- increasing energy efficiency, reversing deforestation, and reducing use of CFCs, for example -- are already of substantial public interest; global warming is often simply another reason for promoting these policies. Many energy efficiency measures are cost-effective, but a number of institutional barriers and market failures would need to be overcome to facilitate their adoption. Benefits include reductions in conventional pollutants, increased energy security, and reductions in the balance of payments deficit, as well as reduced risk of warming. Similarly, reversing deforestation has a wide range of benefits, including maintenance of biological diversity, reduction in soil erosion and reservoir siltation, and local climatic amelioration. Reductions in CFC production beyond those called for in the Montreal Protocol would probably be most significant in reducing the risk of stratospheric ozone depletion, and would also make an important contribution to reducing the risk of climatic change. Some of the options discussed here, such as reduced agricultural emissions, improved biomass production, and heavy reliance on photovoltaics would require further research and development to assure their availability. Relatively small investments in such research could yield important payoffs. The incremental cost of taking actions to limit global warming today may therefore be modest.

The OECD countries can play a leadership role in bringing about reductions in emissions by other countries. Despite great differences between the OECD countries and other countries in sources of emissions and the economic and social constraints on policies to limit them, initiatives by the U.S. and OECD countries can have a significant global impact. U.S. leadership has made important contributions to recent international environmental agreements such as the Montreal Protocol on substances that deplete the ozone layer and the Tropical Forest Action Plan. The U.S. is committed to playing a leadership role in the Intergovernmental Panel on Climate Change recently organized by the World Meteorological Organization and the United Nations Environment Programme. Finally, the U.S. can use its bilateral aid and its influence in multilateral development banks to encourage economic development consistent with reducing the buildup of greenhouse gases.

In contrast to the common notion that limiting global warming would require great sacrifices, we find that many of the policy options that are available for reducing greenhouse gas emissions appear to be attractive in many respects. Policies to begin reducing greenhouse gas emissions must be carefully considered now, notwithstanding the many uncertainties, because the risks of delaying action appear to be large, and the costs of reducing emissions are likely to increase as the time allowed for these reductions is shortened.

FINDINGS

I. Uncertainties regarding climatic change are large, but there is a growing consensus in the scientific community that significant global warming due to anthropogenic greenhouse gas emissions is probable over the next century, and that rapid climatic change is possible.

- A scientific consensus has emerged that greenhouse gases are increasing in concentration in the atmosphere, that, even with a freeze in emissions concentrations will continue to increase, and that, as a result, warming and climate change are likely to occur.

- Uncertainties about global warming abound. The greatest uncertainties concern the ultimate magnitude and timing of warming and the implications of that warming for the Earth's climate system, environment, and economies. The warming that can be expected for a given increase in greenhouse gas concentrations is uncertain due to our inadequate understanding of the climate system. For the benchmark case of doubling carbon dioxide concentrations from preindustrial levels, the equilibrium increase in global average temperature would most likely be in the range of 2-4°C, and could be as little as 1.5°C or as much as 5.5°C.

- A variety of geochemical and biogenic processes that could significantly affect the response of the climate system to greenhouse gas increases have generally been neglected in estimating potential future warming. When all such feedbacks are considered, it is possible that the actual sensitivity of the Earth's climate system to increased greenhouse gases could exceed 5.5°C for an initial doubling of CO_2.

- Because the oceans delay the full global warming that would be associated with any increase in greenhouse gases, significant climatic change could continue for decades after the composition of the atmosphere were stabilized. Assuming that the climate sensitivity to doubling CO_2 is 2-4°C, the Earth is already committed to a total warming of about 0.7-1.5°C relative to the preindustrial era. The Earth has warmed by 0.3-0.7°C during the last century, which is consistent with expectations given the uncertain delay caused by ocean heat uptake.

- Global warming of just a few degrees would represent an enormous change in climate. The difference in mean annual temperature between Boston and Washington is only 3.3°C, and the total global warming since the peak of the last ice age, 18,000 years ago, was only about 5°C.

- Global temperature change estimates are only indicators for the rate and magnitude of climatic change. Climatic changes at the regional level associated with global warming will vary in both magnitude and timing and changes in precipitation and other factors will be as important as changes in temperature.

II. Measures undertaken to limit greenhouse gas emissions would decrease the magnitude and speed of global warming, regardless of uncertainties about the response of the climate system.

- Scenario analyses indicates that greenhouse gas concentrations will show large increases whether the rate of future economic growth and technological change is rapid (the "Rapidly Changing World") or slow (the "Slowly Changing World"). Fossil fuel would play a relatively larger role in raising greenhouse gases in a Rapidly Changing World while agricultural activities and deforestation would play a relatively larger role for the Slowly Changing World.

- If no policies to limit greenhouse gas emissions are undertaken, the equivalent of a doubling of CO_2 occurs between 2030 and 2040 in these scenarios.

- The equilibrium warming commitment for a Rapidly Changing World without policies to limit greenhouse gas emissions is estimated to be 1-2°C by 2000, 3-5°C by 2050, and 5-10°C by 2100 (assuming that the climate sensitivity to doubling CO_2 is 2-4°C). For a Slowly Changing World the equilibrium warming commitment is estimated to be 1-2°C by 2000, 2-4°C by 2050, and 3-6°C by 2100. Estimated warming commitments greater than 5°C may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

- The realized warming in a Rapidly Changing World, without policies to limit greenhouse gas emissions, is estimated to be 2-3°C by 2050, and 4-6°C by 2100 (assuming that the climate sensitivity to doubling CO_2 is 2-4°C). In a Slowly Changing World realized warming is estimated to be about 2°C by 2050 and 3-4°C by 2100.

- The early application of existing and emerging technologies included in this study could lower the commitment to global warming in 2025 by about one-fourth, and the rate of climatic change during the next century could be reduced by at least 60%.

- Although delaying action would allow time to increase knowledge of risks and refine the choice of policies, it could reduce the effectiveness of policy responses. If industrialized countries delay implementation of any response to global warming until 2010 and developing countries delay until 2025, the equilibrium warming commitment in 2050 could increase by 30-40%.

- Stabilizing the commitment to global warming would require cuts in emissions from present levels so significant that currently available and emerging technologies are insufficient to achieve this goal. Consequently, stabilization would require very rapid introduction of existing and emerging technologies and very significant investments in research and development for advanced technologies that reduce greenhouse gas emissions. With such action, equilibrium warming commitment might peak at 1-2°C in 2025 and realized warming may not exceed 1.4°C if the climate sensitivity to doubling CO_2 is 2-4°C.

- If the climate sensitivity of the Earth to increases in greenhouse gases is low, then early application of existing and emerging technologies to limit greenhouse gases could prevent an equilibrium warming commitment of greater than 2°C within a century. If, on the other hand, the true temperature sensitivity of the Earth to doubling CO_2 is 5.5°C or even greater, then without very rapid application of existing and emerging technologies and development of new technologies, the Earth could be committed to a global warming of more than 3°C by as early as 2010 even with application of many existing and emerging technologies to limit greenhouse gases.

III. No single country or source will contribute more than a fraction of the greenhouse gases that will warm the world; any overall solution will require cooperation of many countries and reductions in many sources.

- The U.S. is currently the largest contributor to the greenhouse gas buildup, but its share of global emissions is only about one-fifth of the total. The rest of the OECD and the East Bloc each contribute a similar amount. The relative contribution of the U.S. and OECD countries to total global emissions is likely to decrease over the next century.

- Per capita emissions in developing countries are currently very low, but the share of total emissions contributed by developing countries is expected to increase significantly in the future, and becomes more than 50% by 2025 in the scenarios analyzed.

- All nations will need to adopt measures to slow the buildup of greenhouse gases, if climate change is to be effectively limited. If developing countries do not adopt climate stabilizing policies, then the equilibrium warming commitment in 2050 could increase by about 40% compared to scenarios in which there is global cooperation.

- Technologies developed in the OECD nations could enhance the ability of developing nations to reduce emissions. Efforts to develop technologies that are more efficient and that produce energy from sources other than fossil fuel can make a significant difference in ultimate greenhouse gas emissions throughout the world.

- Energy production and use is currently responsible for almost 60% of increases in the greenhouse effect, followed by chlorofluorocarbons (about 20%), and agricultural practices and deforestation (roughly 10% each). Even the largest source categories, such as automobiles or utilities, however, represent less than 30% each of total greenhouse gas emissions.

- In the immediate term the most effective options to reduce commitments to greenhouse warming are to further reduce chlorofluorocarbons, apply already attractive energy-efficiency technologies, and reduce and then reverse deforestation. Longer-term approaches for reducing the warming commitment would emerge from immediate investments to develop technologies that lower the cost of producing goods and services without producing as high levels of greenhouse gas emissions. Promising technologies include advanced materials, thin-film photovoltaics, and biomass-fired turbines.

- Neither energy efficiency nor non-fossil fuels alone would be sufficient to greatly limit greenhouse gas emissions in the long term; both will be necessary.

IV. A wide range of policy choices is available to reduce greenhouse gas emissions while promoting economic development, environmental, and social goals.

- Industrialized and developing countries could limit the buildup of greenhouse gases in a manner consistent with economic development and other environmental and social goals. In industrialized countries, acid rain, urban ozone, and dependence on imported energy could be reduced as part of an overall strategy that reduces greenhouse gas emissions. Energy efficiency improvements are already essential in developing countries to reduce capital requirements for the power sector, and efforts to halt deforestation will provide many long-run economic and environmental benefits.

- If limiting the greenhouse gas buildup is desired, government action will be necessary. Market prices of energy from fossil fuels, products made with CFCs, forest and agricultural products, and other commodities responsible for greenhouse gas emissions do not reflect the risks of climate change.

- The most direct means of allowing markets to incorporate the risk of climatic change is to assure that the prices of fossil fuels and other sources of greenhouse gases reflect their full social costs. It may be necessary to impose emission fees on these sources according to their relative contribution to global warming in order to accomplish this goal. This would also raise revenues that could finance other programs. The degree to which such fees are accepted will vary among countries, but acceptability would be enhanced if fees were equitably structured.

- Regulatory programs would be a necessary complement when pricing strategies are not effective or produce undesirable impacts. In the U.S., greenhouse gas emissions are influenced by existing federal regulatory programs such as those designed to control air pollution, increase energy efficiency, and recycle solid waste. Reducing greenhouse gas emissions could be incorporated into the goals of these programs. New programs could focus directly on reducing greenhouse gas emissions through requirements such as emissions offsets (e.g., tree-planting), performance standards, or marketable permits.

- The best ways to avoid producing greenhouse gases cannot be anticipated; accelerated investment in a range of options is necessary if policy makers want to assure that better and less costly options will be available in the future.

- Government policy is already exerting considerable influence on the rate of growth in greenhouse gases. Policies adopted to reduce CFC production will reduce the rate of greenhouse gas buildup. Policies that have been adopted or are under consideration to promote greater use of coal, reduce required improvements in automobile efficiency, and subsidize electricity consumption, may significantly accelerate the rate of greenhouse gas emissions. A combination of factors that increase greenhouse gas emissions could accelerate commitments to global warming by as much as 60% in 2050 relative to the Rapidly Changing World scenario.

- U.S. leadership has made important contributions to recent international environmental agreements, such as the Montreal Protocol on Substances that Deplete the Ozone Layer and the Tropical Forest Action Plan. The U.S. government is committed to playing a key role in the Intergovernmental Panel on Climatic Change (IPCC) established under UNEP and WMO auspices. The U.S. can also promote desirable changes in energy and environmental policy in developing countries through judicious use of its bilateral aid programs and its influence on loans extended by multilateral development banks. Finally, domestic initiatives could foster international cooperation by demonstrating a commitment to respond to global climatic change.

*U.S. GOVERNMENT PRINTING OFFICE:1989-620-710:00960